

Words to communicate concepts

Brookhaven National Laboratory

Relativistic Heavy Ion Collider

Understanding
Observation
Experiment
Theory
Light Wave
Photon

small, very small
very fast

Mechanics:
Classical
Quantum
Relativistic

The Nucleus

Nucleons:
Proton & Neutron
Radioactive Decay

Particles & Fields

Parton: Quarks
and Gluons

Baryons, Hadrons
 π Meson (pion)

Leptons

Electron e^- Positron e^+
Muon μ^- μ^+ Tau τ^- τ^+
Neutrinos ν_e ν_μ ν_τ

Strong suppression
Dense final state
Anisotropic Flow
Nearly perfect fluid
Asymptotic Freedom
Phase Transitions
Deconfinement
Early Universe
(Big Bang)

The Atom
Hard Sphere Model
Plum Pudding Model
Nuclear Atom
Soft/Hard Scattering
Electron Wave
Wave-Particle Duality
Quantum Mechanics

Direct and Virtual Photons
Hottest Temp. Measured

Modern Physics:

Understanding the very small and the very fast

Brant M. Johnson

- ◆ **Atomic, Nuclear, and Particle Physicist**
- ◆ **Plasma, Beams, and Atomic Physics Editor**
- ◆ **Publications Coordinator for PHENIX Collaboration**
- ◆ **Chair, Physics Department ESSH Committee**
- ◆ **Former-Chair, RHIC & AGS Users' Executive Com.**
- ◆ **Former-Chair, National User Facility Organization**
- ◆ **Outreach and Educational Program Speaker**
- ◆ **Helping to develop K-12 common core standards**

The National Governors Association (NGA) and Council of Chief State School Officers (CCSSO) are committed to a state-led process -- the Common Core State Standards Initiative (CCSSI)

Goal: All students should graduate from high school prepared for the demands of postsecondary education, meaningful careers, and effective citizenship.

English and Language Arts, Mathematics, and Literacy in History/Social Studies, Science, and Technical Subjects.

Experts understand the core principles and theoretical frameworks of their field.

Their retention of detailed information is aided by an understanding of its placement in the context of these principles and theories.

Learning to understand science or engineering in a more expert fashion requires development of an understanding of how facts are related to each other and to overarching core ideas.

Physics Week (continued)

Tuesday

Milind Diwan -- Physics at BNL

Christoph Montag -- Relativistic Heavy Ion Collider (RHIC) Tunnel Tour

Gene van Buren -- STAR Detector Tour

Paul Sorenson -- Physics Colloquium “Sambamurti Lecture”

Wednesday

Marc- Andre Pleier -- Large Hadron Collider (LHC) and the Atlas Detector

Peter Wanderer -- Magnet Factory tour

NOAA at BNL -- Doppler Radar/Weather Balloon Launch

Thursday

William Sherman -- Center for Functional Nanomaterials (CFN)

Stefan Tafrov and Michael Sivertz -- NASA Space Radiation Lab (NSRL)

Friday

Hakeem Oluseyi -- Near-Field Cosmology

Cecilia Hanke-Sanchez -- Physics of National Synchrotron Light Source

Learning (Memorizing) vs Understanding (Knowing)

A child can learn or memorize that:

$$1 + 1 = 2 \quad \text{or} \quad 2 - 1 - 1 = 0$$

but 1, 2, and "zero" are abstract concepts.

For a child: Understanding comes from experience. Give a child one toy and then another. The child understands having fun playing with one + one equals two toys.

Subtraction: Take the two toys away abruptly: Now the child now knows what "zero" means and may even cry based on true understanding.

Understanding Physics

Usual Definition:

Physics is the Study of Matter

Ancient Meaning:

**Physics is from the Greek word PHYSIS,
which means:**

The attempt to “see” the nature of things

Small → smaller → smaller → smallest?

People →

Organs →

Cells →

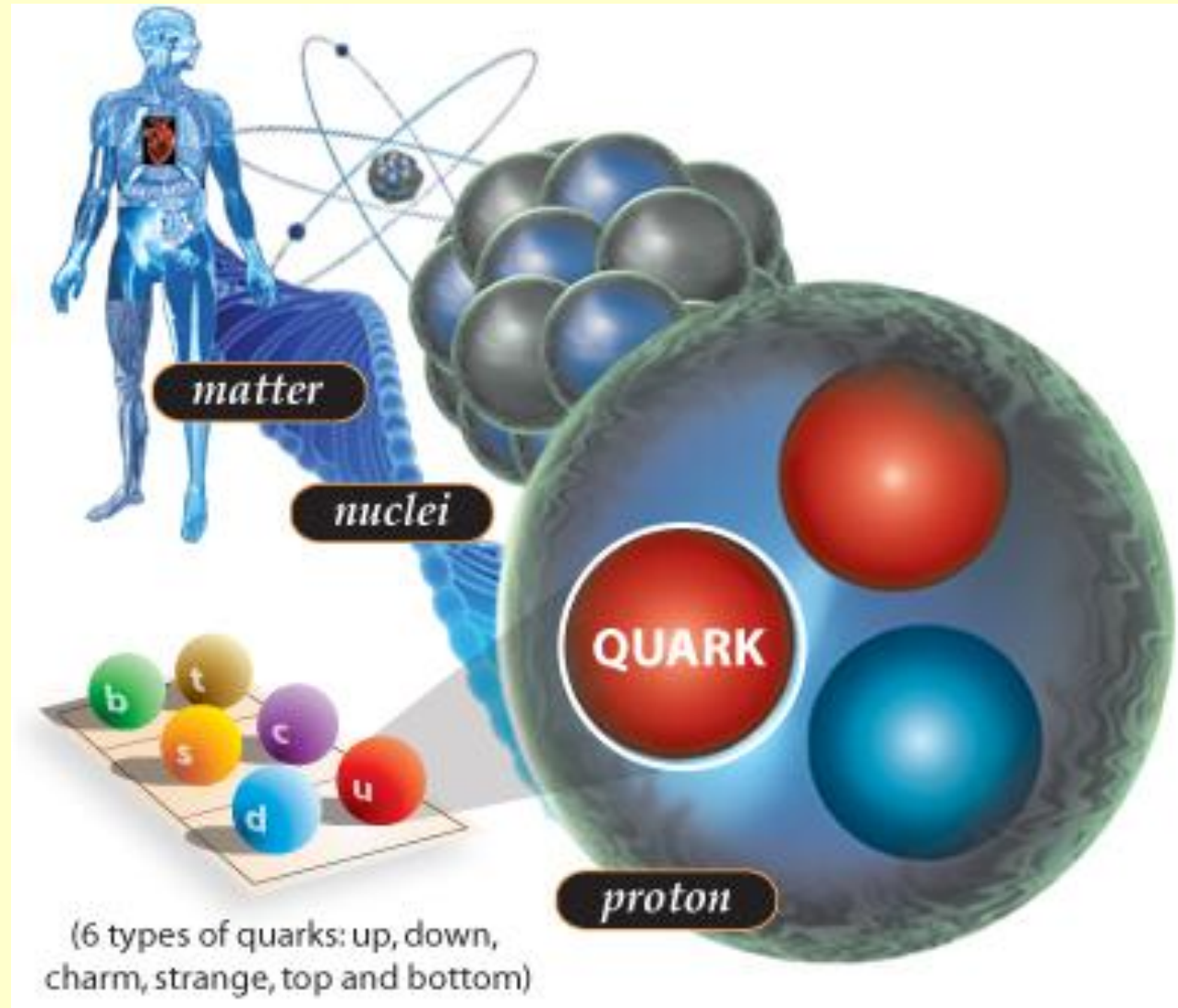
Molecules →

Atoms →

Electrons
and nuclei →

Protons
and neutrons →

Quarks and gluons →



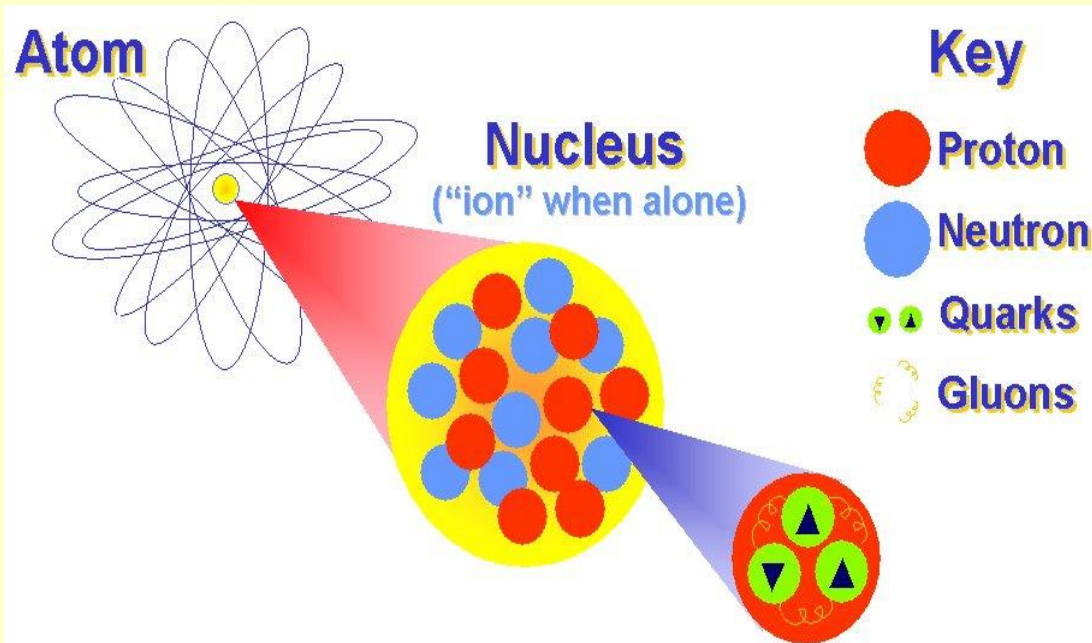
A ... sense ... of ... Wonder

Small,

→ → →

smaller,

→ → →



even smaller,

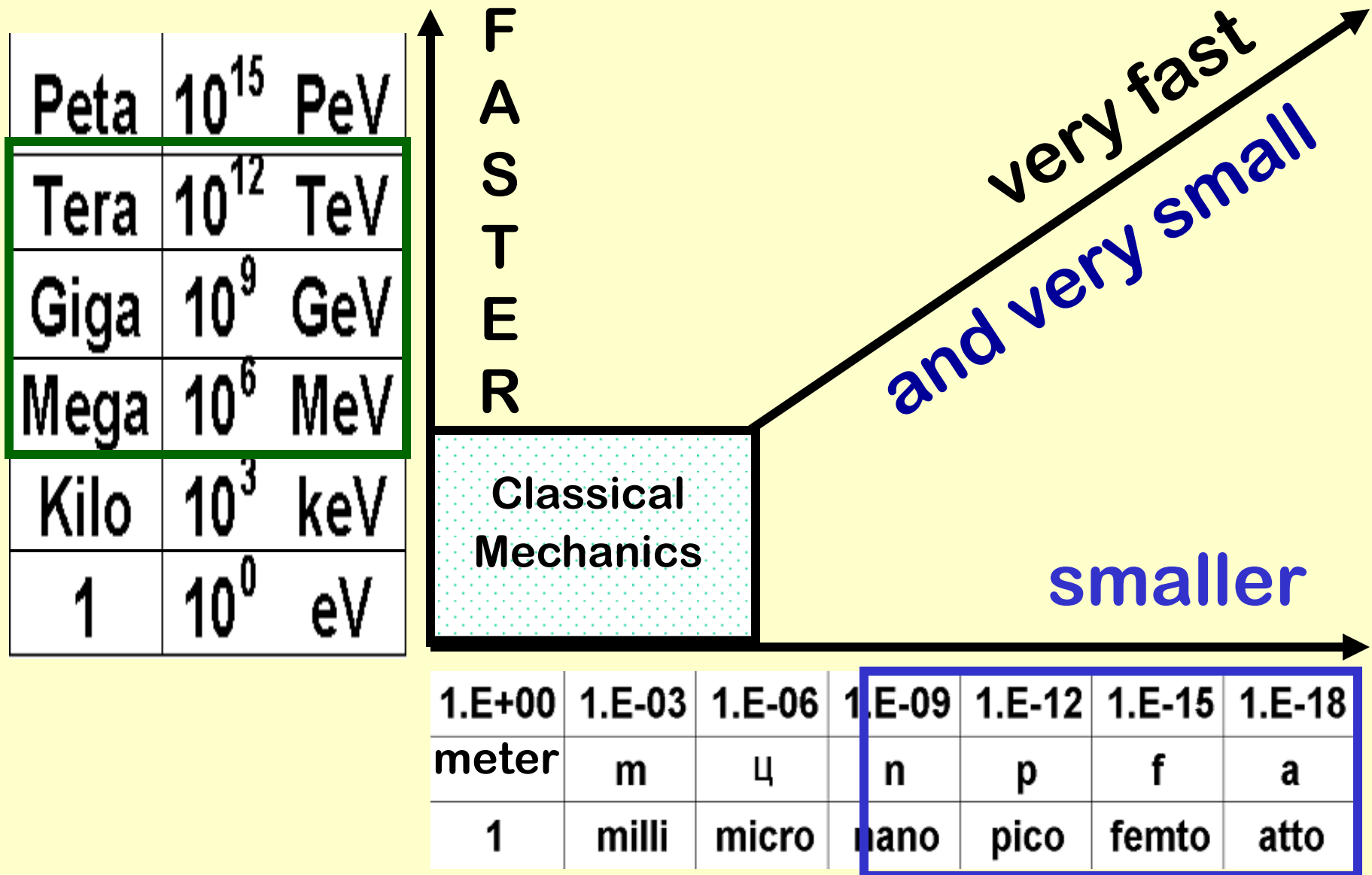
→ → →

and smaller

→ → →

smallest?

The Very Fast and the Very Small

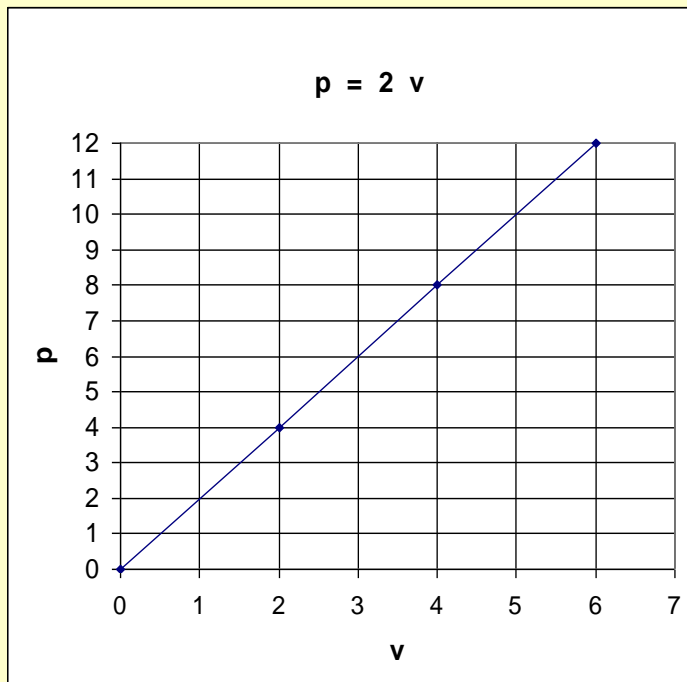


Understanding Linear Momentum

In Classical Physics (the large and the slow):
linear momentum (p) equals mass (m) times velocity (v)

$$p = mv \quad (\text{linear equation: } y = ax)$$

Visualize example,
If $m = 2$, then $p = 2v$



Ah, but how can we truly
UNDERSTAND momentum?

Force is change in momentum
w.r.t. time.

$$F = dp / dt$$

If I offer to toss to you either a
tennis ball or a bowling ball at
the same velocity, which one
would you be willing to catch?

Understanding Classical Energy

In Classical Physics (the large and the slow), Potential Energy is mass (m) times gravitational const, (g) times height (h):

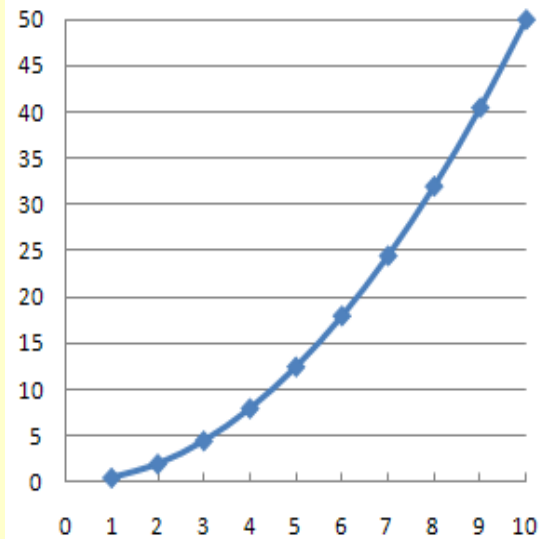
$$\text{P.E.} = mgh$$

Kinetic Energy is $\frac{1}{2}$ mass (m) times velocity (v):

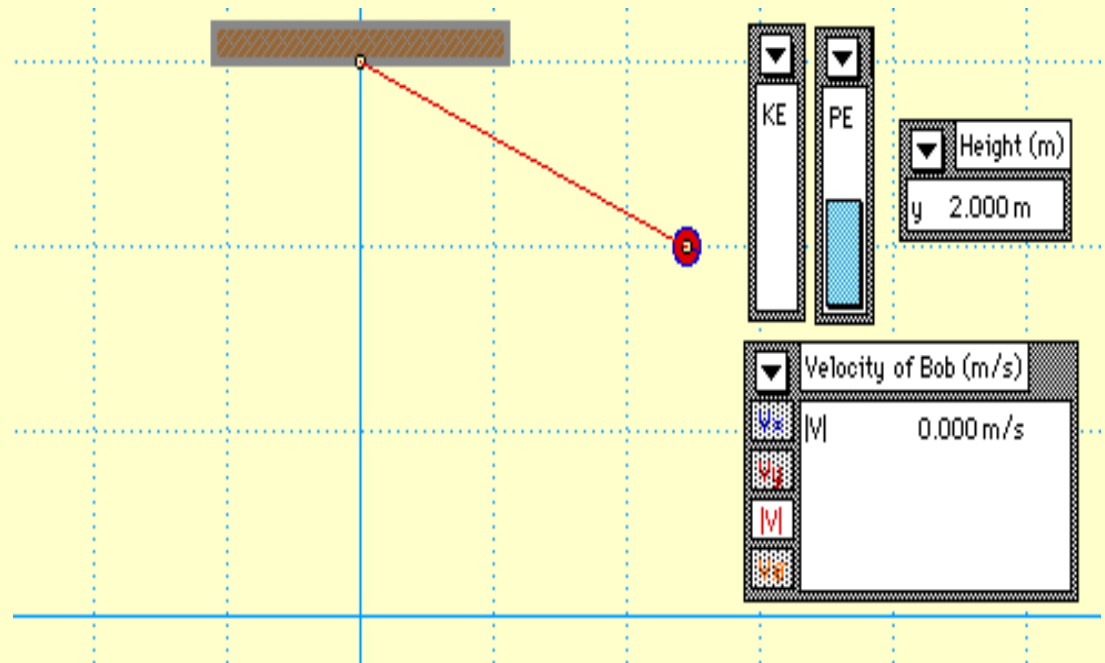
$$\text{K.E.} = \frac{1}{2} m v^2$$

Total Energy (E_{total}) is the sum: $\text{P.E.} + \text{K.E.} = E_{\text{total}}$

K.E.

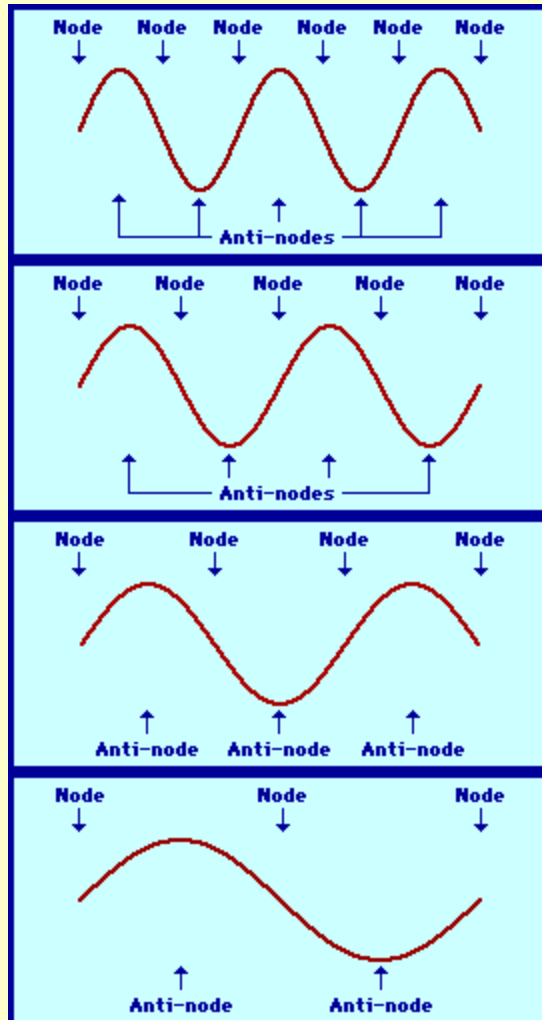


v



Understanding Waves

$$(1/\lambda \propto \nu \propto E)$$



λ wavelength	ν frequency	E Energy
-------------------------	--------------------	-------------

$$2/5 \lambda_0$$

$$5/2 \nu_0$$

$$5/2 E_0$$

$$1/2 \lambda_0$$

$$2 \nu_0$$

$$2 E_0$$

$$2/3 \lambda_0$$

$$3/2 \nu_0$$

$$3/2 E_0$$

$$\lambda_0$$

$$\nu_0$$

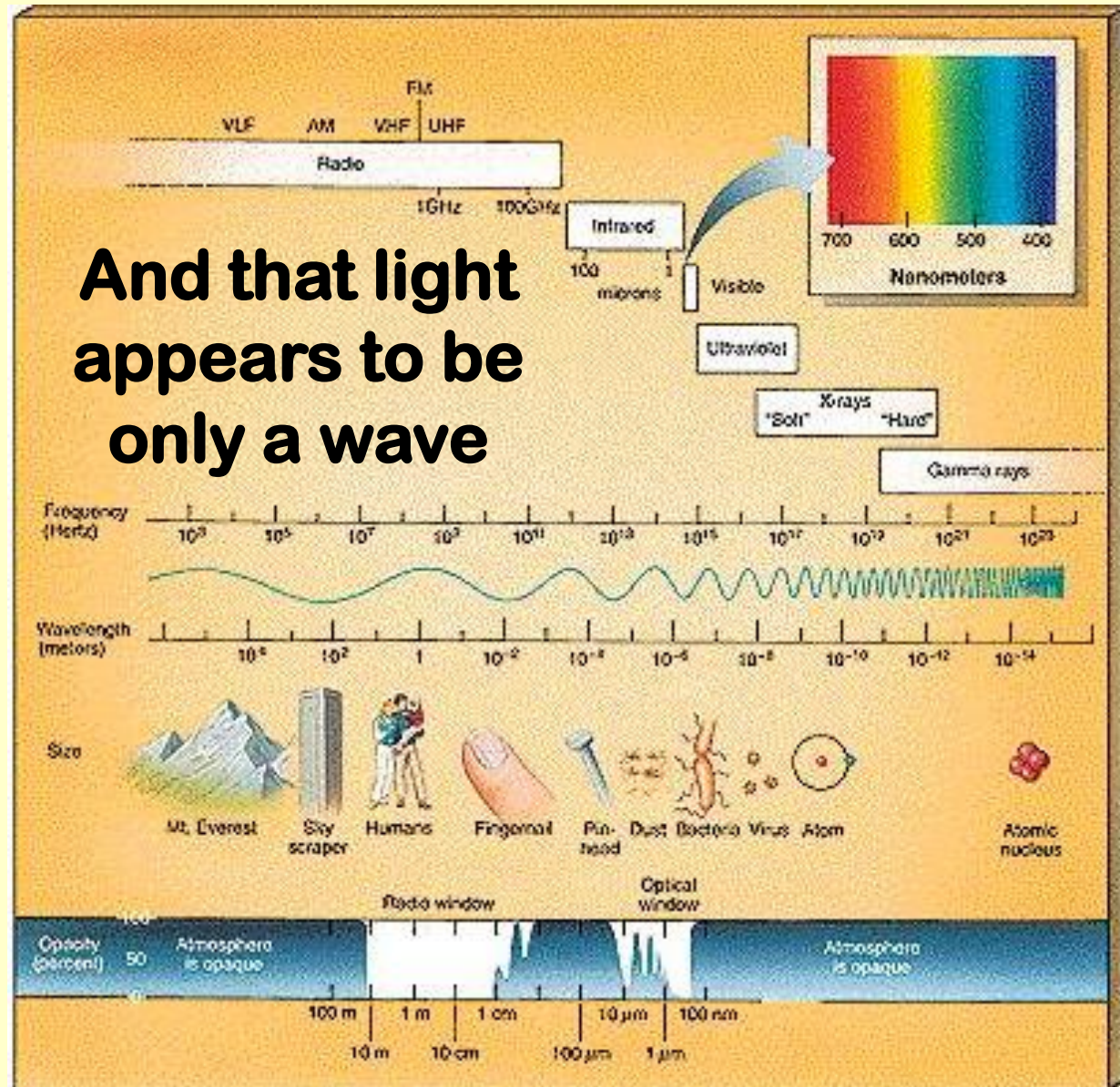
$$E_0$$

Conservation of Energy and Momentum – Light

We observe in nature that for “particles” in motion energy and momentum are conserved

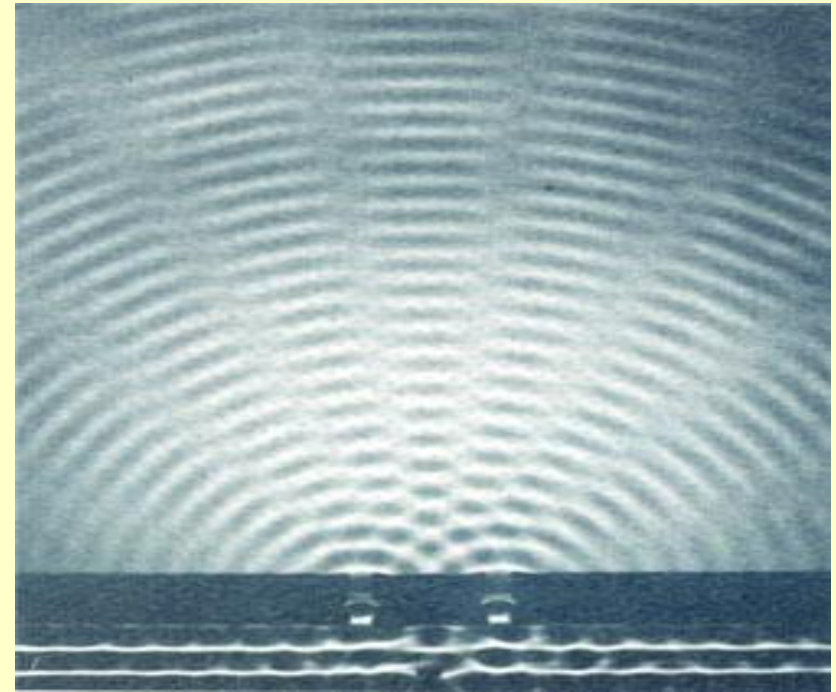
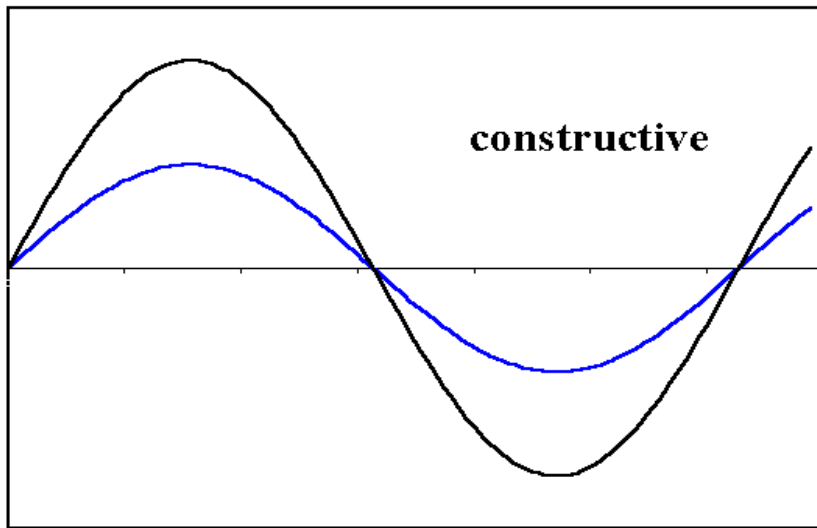


And that light appears to be only a wave



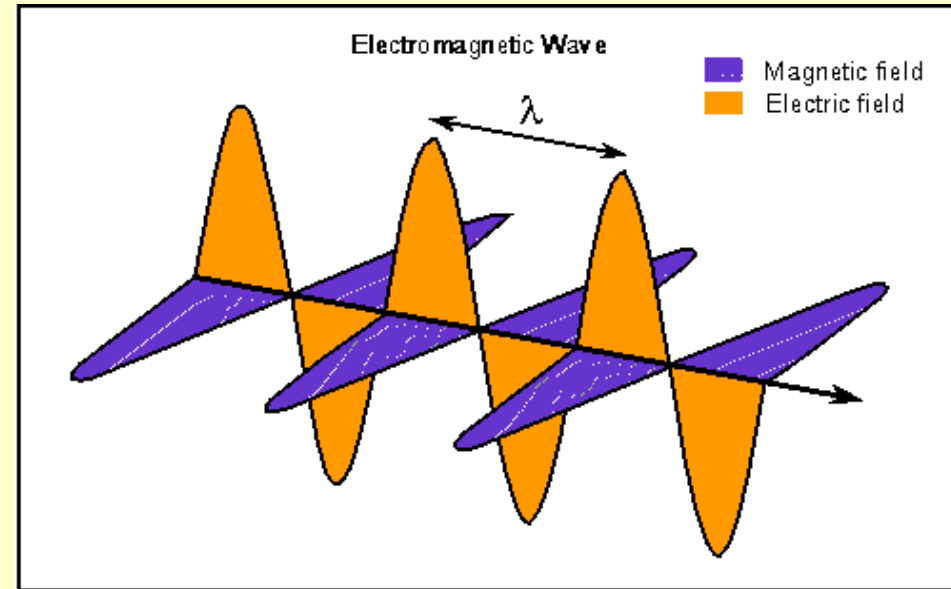
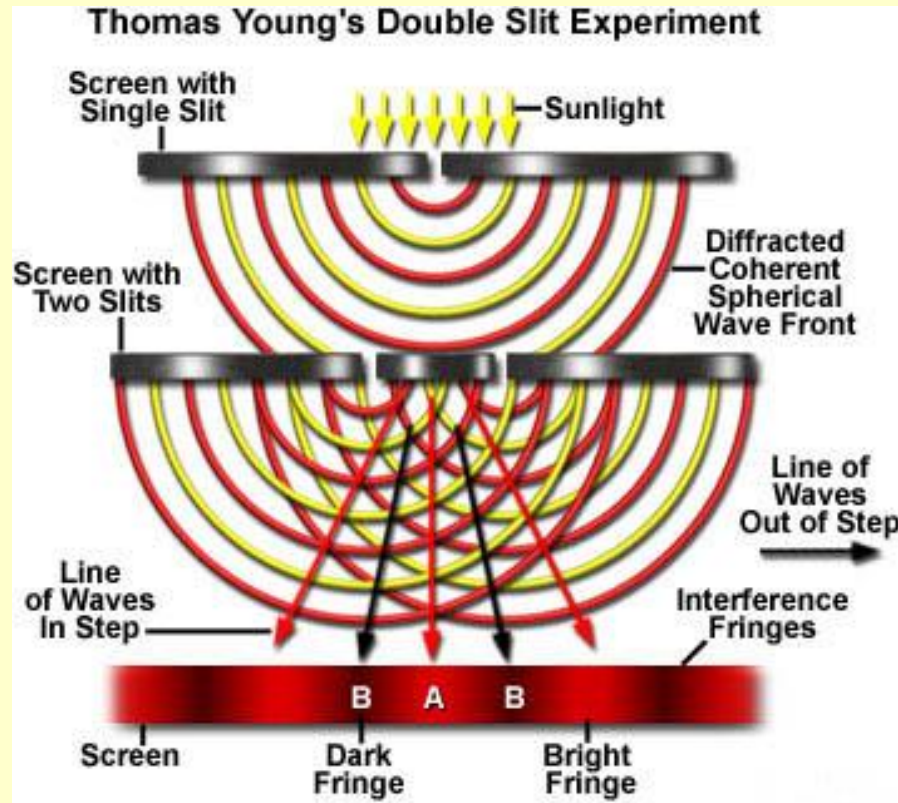
Waves and Diffraction

A wave moving through a single slit produces a circular wave pattern caused by diffraction. (pebble dropped in a pond).



Waves passing through two slits cause constructive and destructive interference, producing a diffraction pattern.

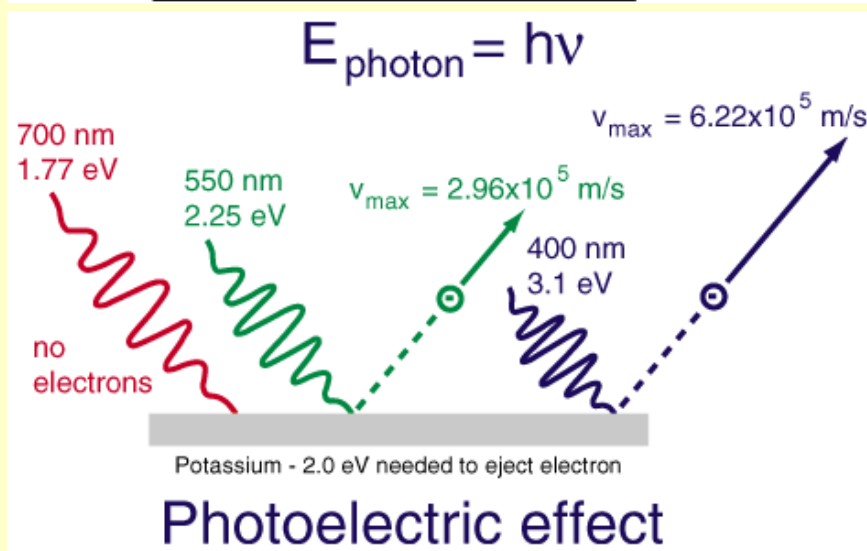
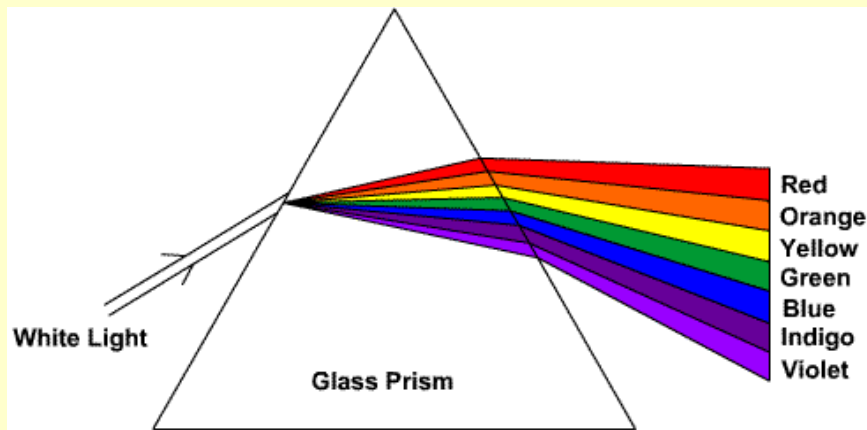
Diffraction shows light is a wave



Young's Double-Slit Experiment
in 1803 proved that light
acts like a wave

But!
It did not
prove that
light is only
a wave.

Photons (particles of light or quanta)



1905 Albert Einstein

Explained the photoelectric effect using a mathematical description that assumed it was caused by absorption of quanta of light (now called photons).

Einstein showed how the “particles-of-light” concept explained the photoelectric effect in terms of absorption of discrete quanta.

Einstein's explanation of the photoelectric effect won him the Nobel Prize in Physics in 1921.

$$E_e(\text{red})=0 \quad E_e(\text{green})=0.25 \text{ eV} \quad E_e(\text{violet})=1.1 \text{ eV}$$

How do we advance our understanding of nature?

Aristotle (384 – 322 BCE): “Those who wish to succeed must ask the right preliminary questions.”

“Aristotle's Fundamental Propositions:

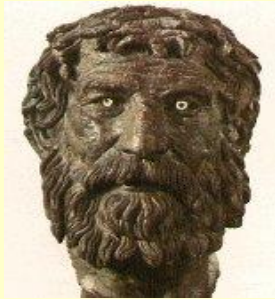
- **Logic is the essential method of all rational inquiry**
- **Theory should follow upon the empirical observation of nature and things.**

Yogi Berra: You can observe a lot by watching.

***The test of all knowledge is experiment.
EXPERIMENT is the SOLE JUDGE
of SCIENTIFIC TRUTH. -- Richard P. Feynman***

Asking a “right” preliminary question

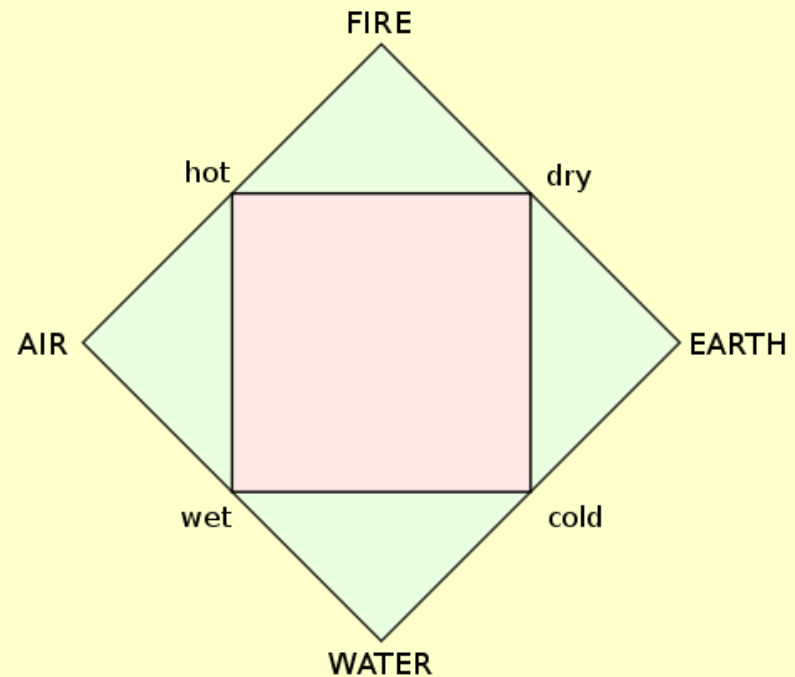
What are the Elements of Nature?



Empedocles (490-430 BCE) first classified the elements as fire, air, earth, water (Chinese added: wood, metal)

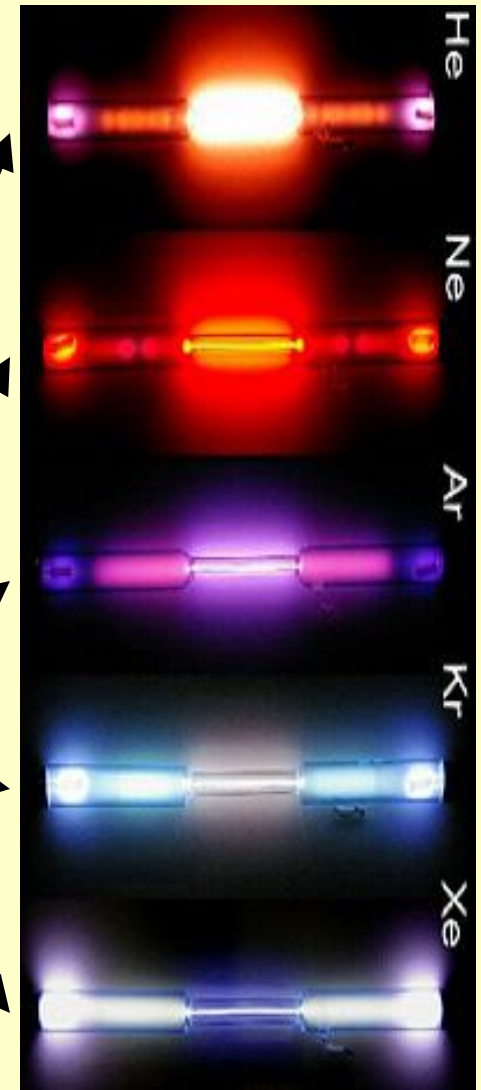


(c) Andy Brice 1998



Periodic Table of the Elements

H																			He
Li	Be												B	C	N	O	F		Ne
Na	Mg	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn		Ga	Ge	As	Se	Br		Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn		Ga	Ge	As	Se	Br		Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd		In	Sn	Sb	Te	I		Xe
Cs	Ba	*	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg		Tl	Pb	Bi	Po	At		Rn
Fr	Ra	**	Rf	Ha	Unh	Ns	Hs	Mt	Uun	Uuu	Uub		Dy	Ho	Er	Tm	Yb		
			La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb		Dy	Ho	Er	Tm	Yb		
			Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk		Cf	Es	Fm	Md	No		



electrons (-1), protons (+1), neutrons (0)

Noble gases

What do we know about atoms?

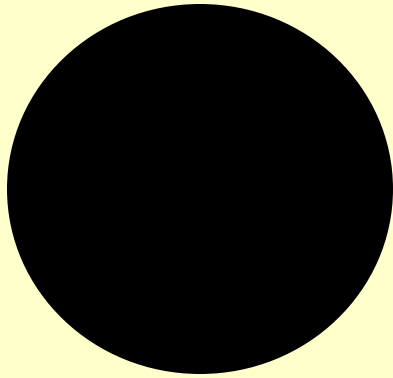
Things that we know today about

ATOMS

1. Very small: About 0.1nm across
2. Stable: Atoms can last forever
3. Electrically neutral (no net charge)
4. Emit and absorb light at discrete wavelengths and energies

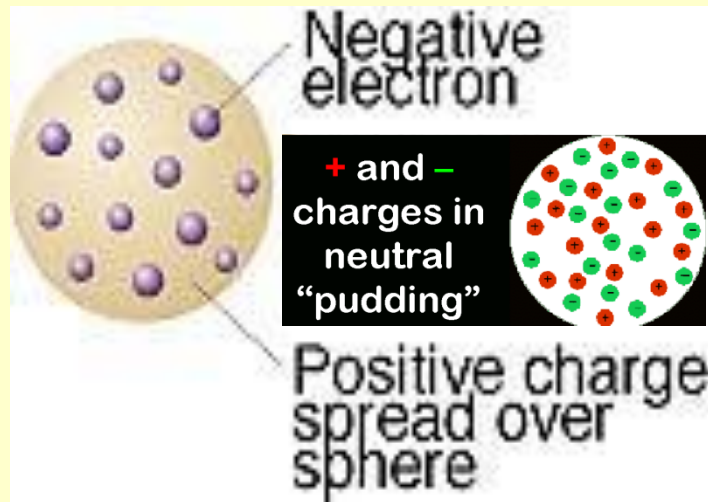
Early Atomic Models: Hard Sphere; Plum Pudding

5th Century B.C. Hard Sphere Model



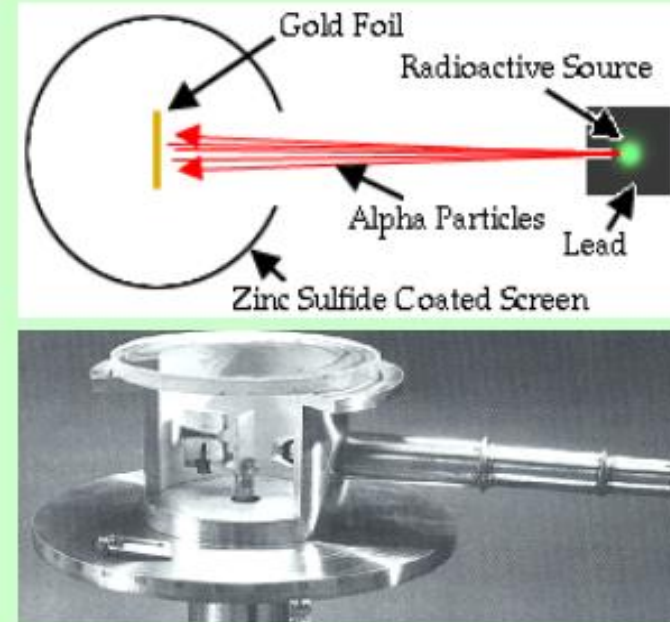
Greek Philosopher
Democritus
proposed that every
form of matter is
made of very tiny
pieces or indivisible
building blocks,
which he called
ATOMS.

1897 – Plum Pudding Model



J. J. Thomson reasoned
that because electrons
comprise only a very
small fraction of the
mass of an atom, they
probably were
responsible for an
equally small fraction
of the atom's size.

1907 – Testing the Plum Pudding Model

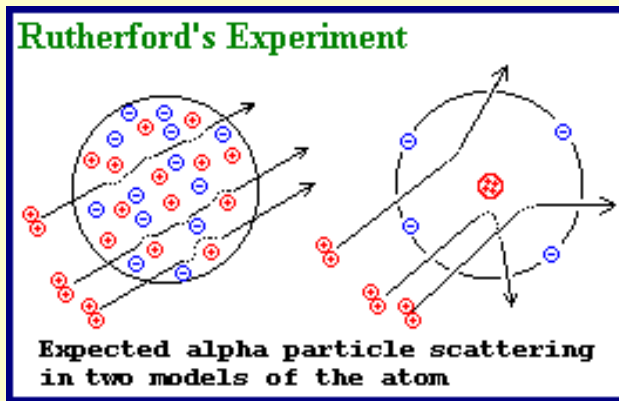


Ernest Rutherford sent
alpha particles from a
radioactive source
through a thin foil
to observe the distribution
of scattered particles.

Nuclear Atom; Soft scattering; Hard scattering

1907 – Nuclear Atom

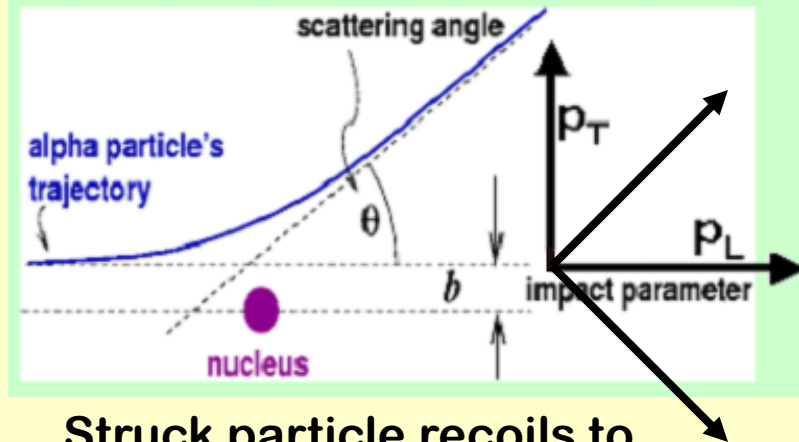
Rutherford expected the alpha particles to be only slightly deflected when passing through the “plum pudding” atoms.



Instead they were deflected to large angles. This proved that a massive nucleus was at the center.

Rutherford was astonished and said: “It was almost as incredible as if you had fired a 15-inch shell at a piece of tissue paper and it came back and hit you.”

Transverse Momentum p_T
Longitudinal Momentum p_L



Struck particle recoils to conserve linear momentum (total p_T is always 0)

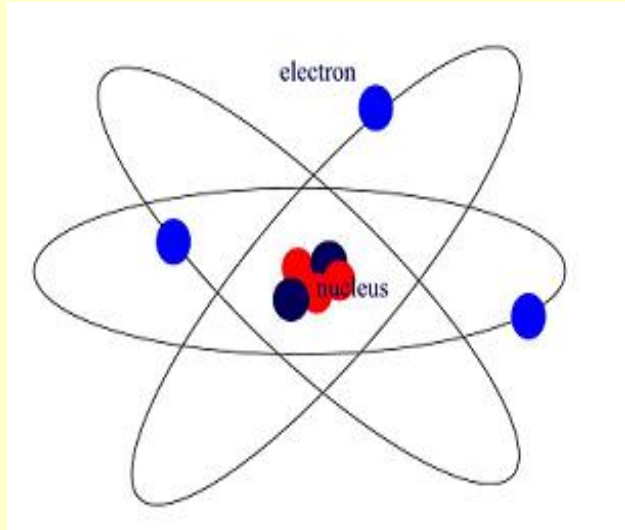
Soft Scattering: Low p_T

Hard Scattering: High p_T

(hard scattering implies substructure, that is something smaller inside).

Bohr Planetary Model – DeBroglie Electron Waves

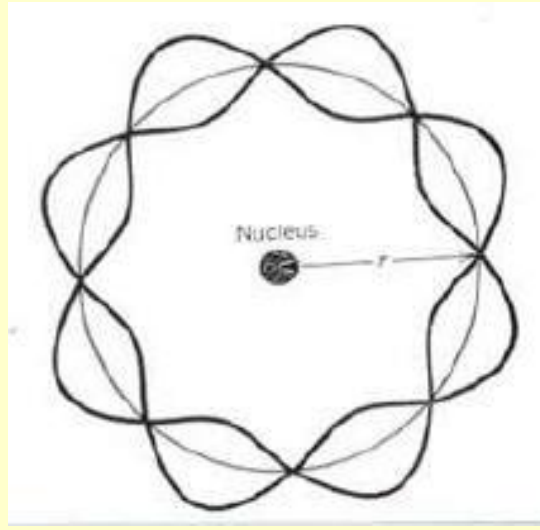
1913
Planetary Atom



Neils Bohr suggested that the electrons in an atom might be orbiting the nucleus, much like the planets in our solar system orbit the sun

but in non-radiating orbits!

1923
Standing Electron Waves

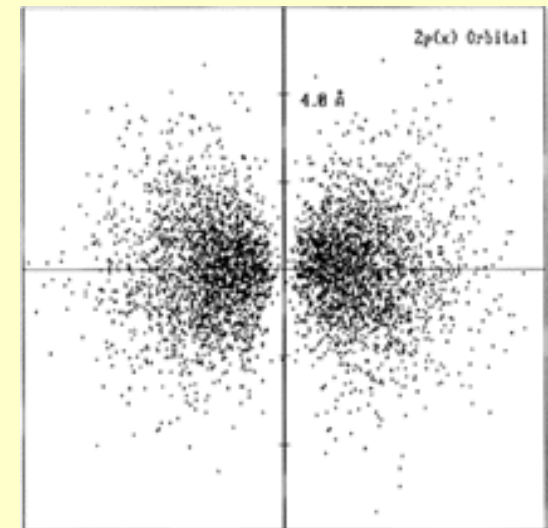


Louis de Broglie proposed the fascinating idea that matter actually consists of waves.

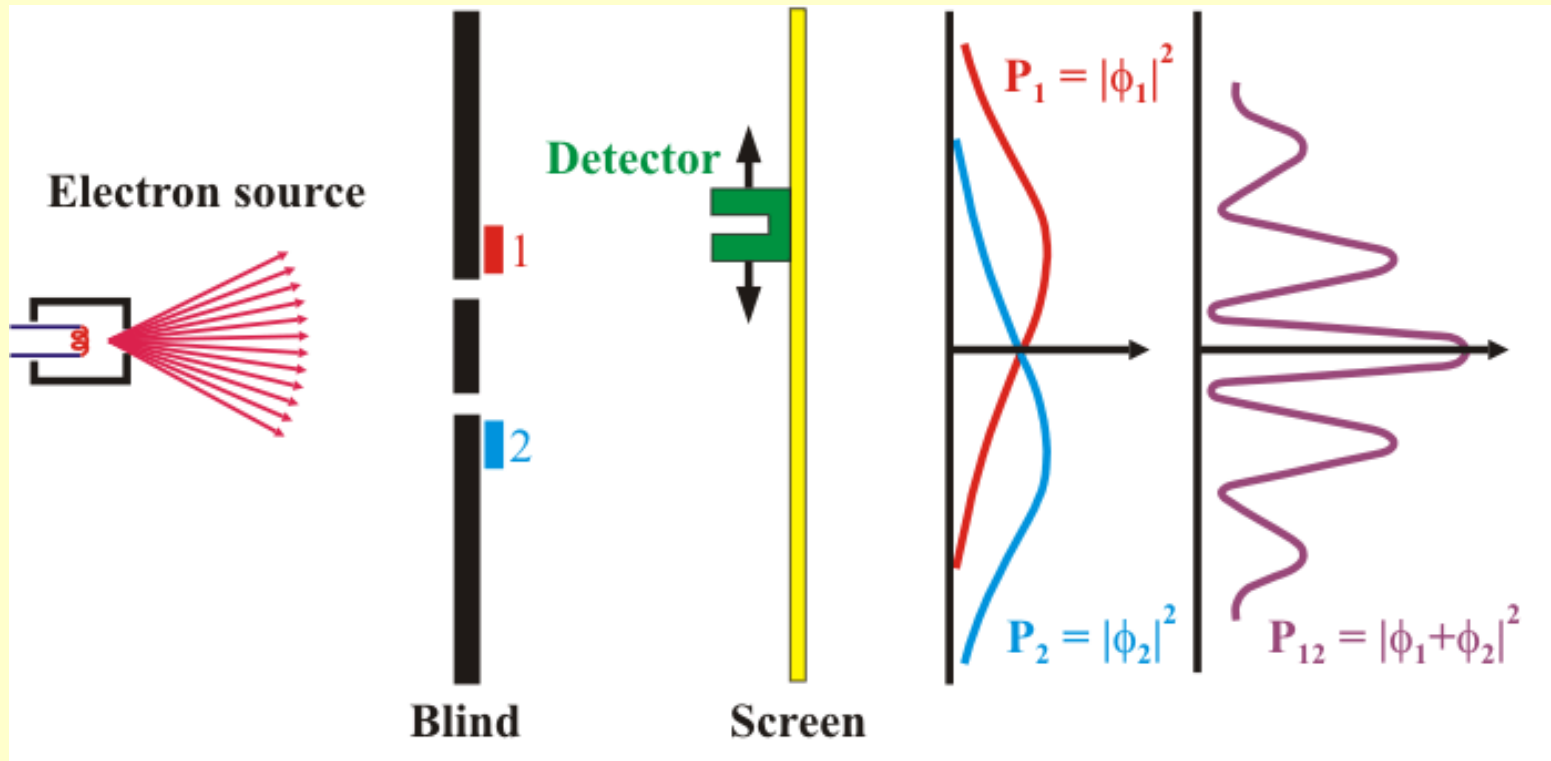
For example, the electrons in an atom form standing electron waves.

1926
Wave Mechanics

Erwin Schroedinger showed later that probability distributions can tell where the particle is most likely to be.



Electron Diffraction



Wave-Particle Dualism: Electrons exhibit both wave and particle aspects.

Energy: $E = hf = h v_e / \lambda$

Momentum: $p = hf / v_e = h / \lambda$

Wave-Particle Dualism

Experiments have shown that things we usually think of as waves also act like particles and that things we usually think of as particles also act like waves.

Light Wave \leftrightarrow Photon
Electron Wave \leftrightarrow Electron

This does NOT mean that all things are “wavicles”
An electron (e.g., one bound in an atom) acts as either 100% particle or 100% wave.

Principle of Complimentarity: No experiment can simultaneously show both wave and particle aspects at the same point in space and time.

Quantum Mechanics Quotes

Most physicists are very naive; most still believe in real waves or real particles.
– *A. Zeilinger*

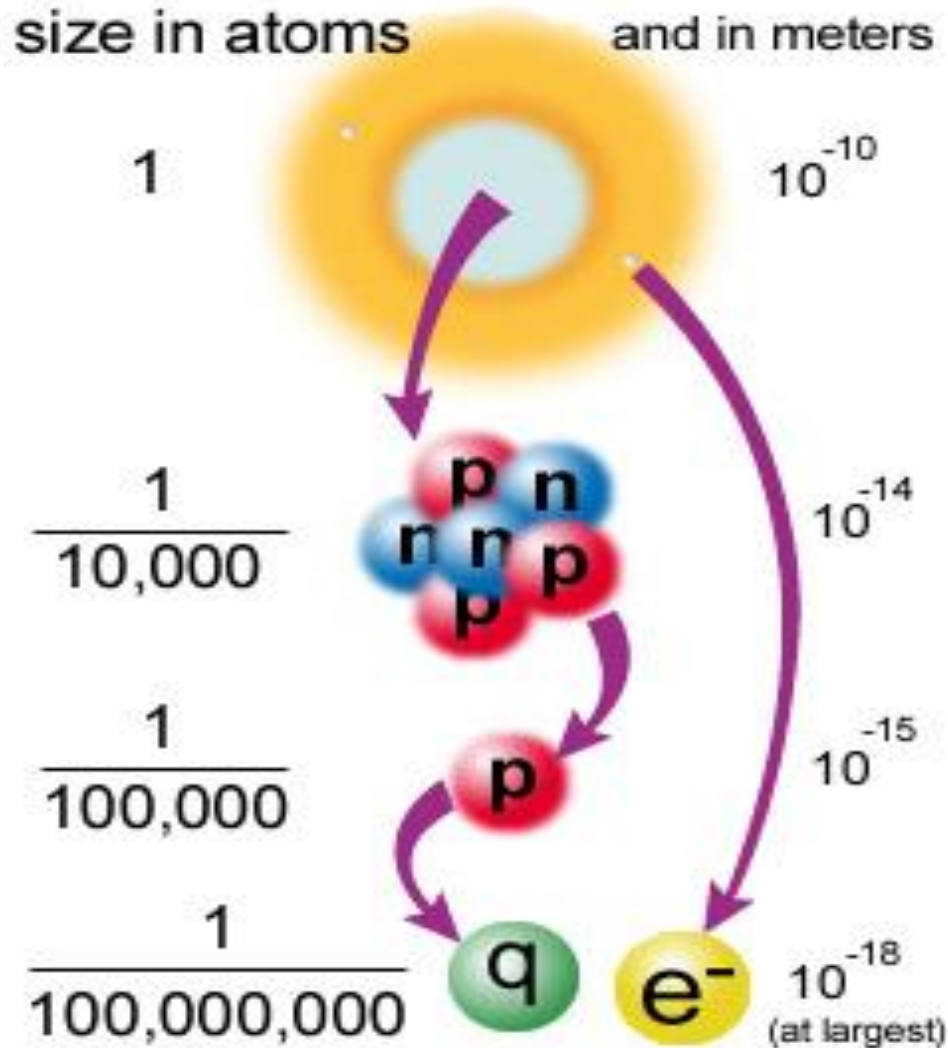
Quantum phenomena are neither waves nor particles, but are intrinsically undefined until the moment they are measured.
– *J. Wheeler*

God does not play dice with the universe. – *A. Einstein*

It is not the job of scientists to prescribe to God how He should run the world.
– *N. Bohr*

Bohr said that if you aren't confused by quantum mechanics, then you haven't really understood it
– *J. Wheeler*

Atom, Nucleus, Nucleon, Parton, Electron

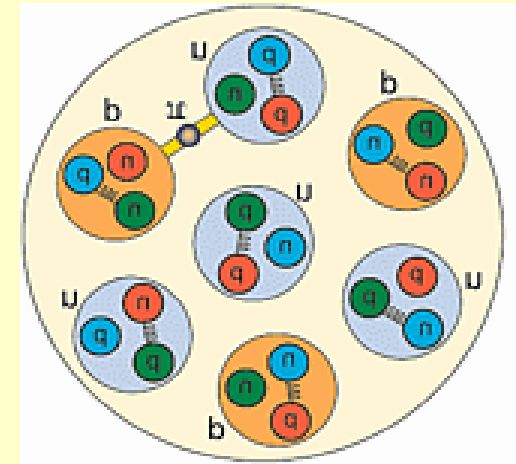


smaller parts

Atom:
Nucleus & Electrons
~ 0.1 nm

Nucleus ~ 10 fm

Nucleons:
Protons
Neutrons
~1 fm



Partons
Quarks & Gluons
(Size of Electrons ~ 1 am)

Mechanics: Classical, Quantum, Relativistic

Mechanics	Energy	Momentum	Conserved
Classical [Newtonian] (human size and speed)	Kinetic: $E = 1/2 m v^2$ Potential: $T = m g h$ Total: $E = T + K$	Linear: $p = m v$ Orbital: $l = m v r$	Energy, Mass, Momentum, Waves, Particles, Size, Time
Quantum (very small)	$E = h \nu$ $= h c / \lambda$ (Wave-Particle Duality)	$p = h / \lambda$	Energy, Momentum [stuff is not!]
Relativistic (very fast)	$E = m c^2 = \gamma m_0 c^2$ $= \sqrt{p^2 c^2 + m_0^2 c^4}$	$p = m v$ $p = \gamma m_0 v$	Mass/Energy, Momentum [stuff is not!]
$\gamma = 1 / \sqrt{1 - v^2 / c^2}$			

Main Message:

Total energy and momentum are always conserved, but **for very small (quantum)** and **very fast (relativistic)** mechanics, the “stuff” that carries the energy and momentum is not conserved and not even well defined.

$$E = h \nu$$

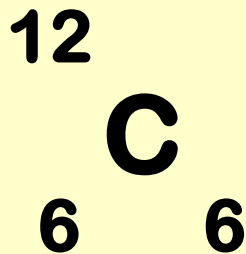
$$= h c / \lambda$$

$$E = m c^2$$

Elements and Isotopes

Atomic Mass (A)
= Z + N

Element (C):



Atomic Number (Z)
= number of
protons (p)

Neutron Number (N)
= number of
neutrons (n)

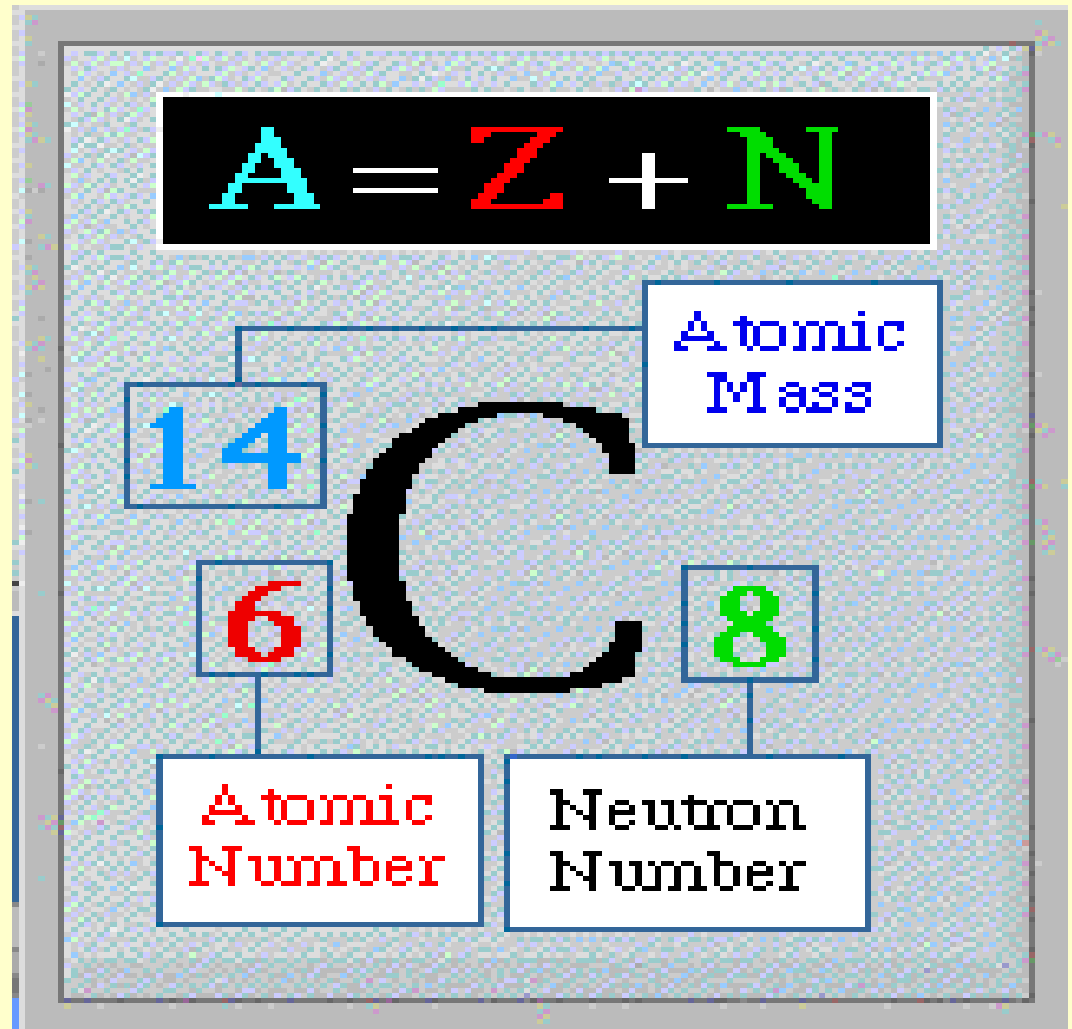
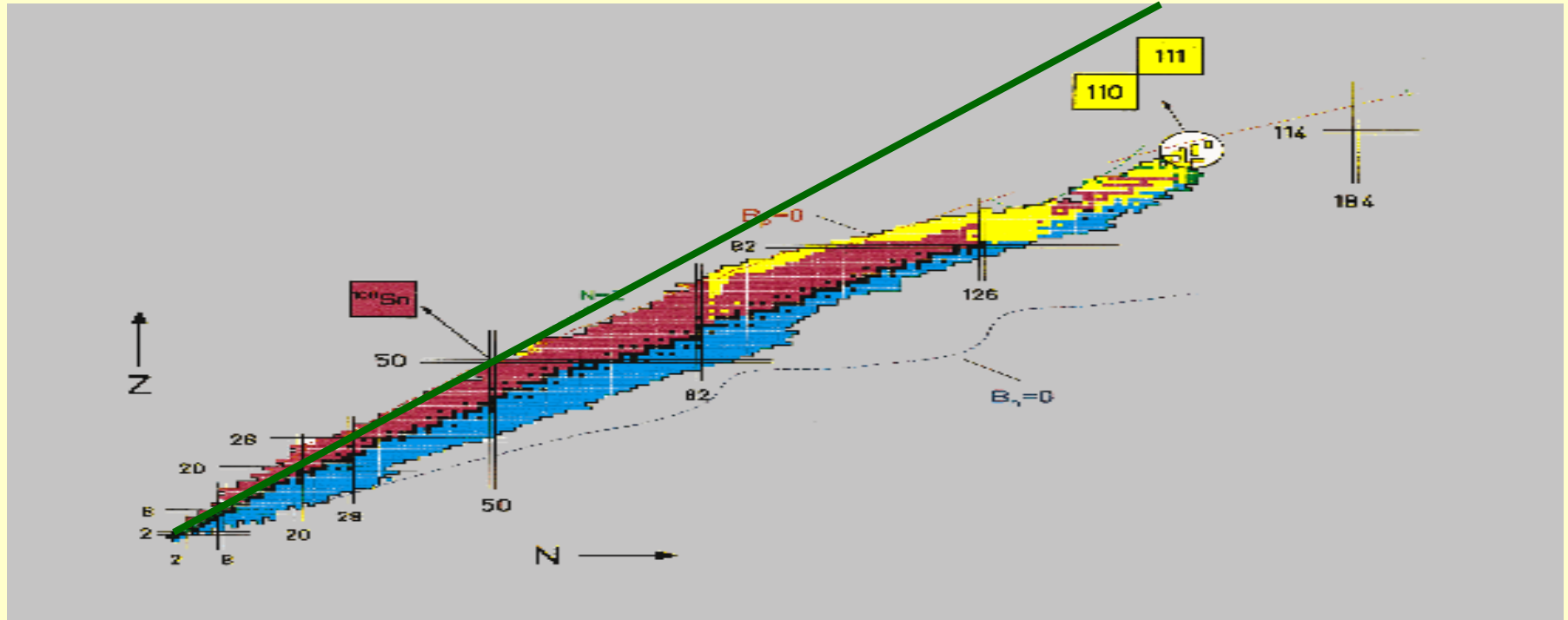


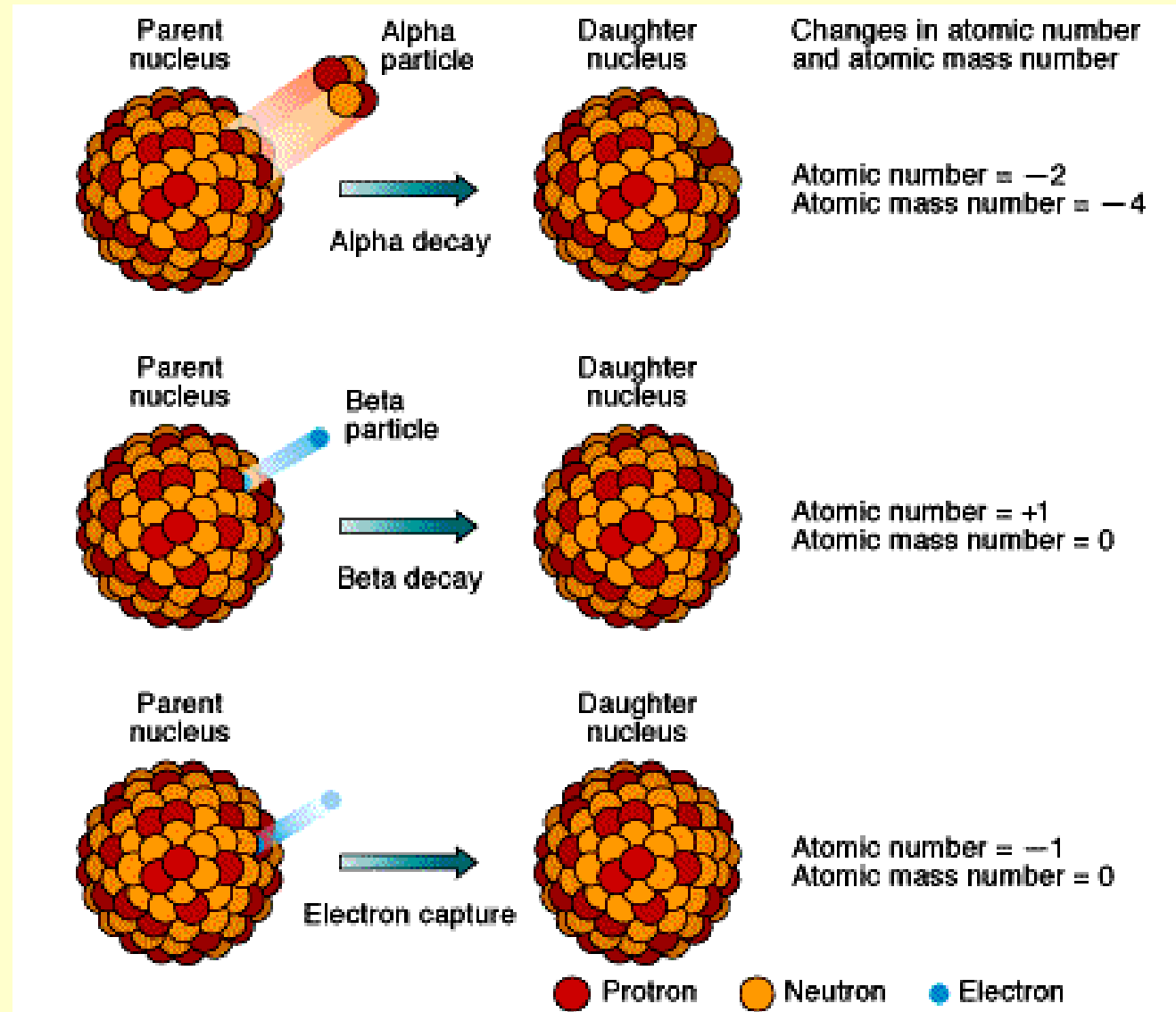
Chart of the Nuclides (Z vs. N)



Isotopes are nuclei with the same Atomic Number Z (protons), but different Neutron Number N (neutrons). Light elements usually have about the same N as Z , but heavier elements have more neutrons (higher N) than protons (lower Z).

Radioactive decay can change Z or M

Some forms of radioactive decay can change the atomic number (Z) or mass (M) of the primary nucleus.



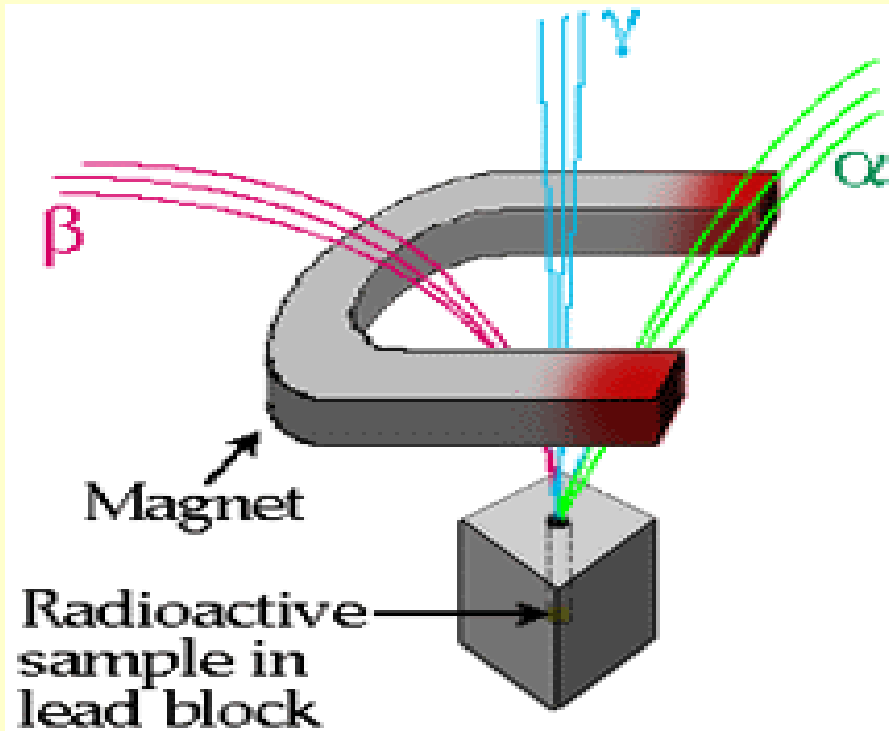
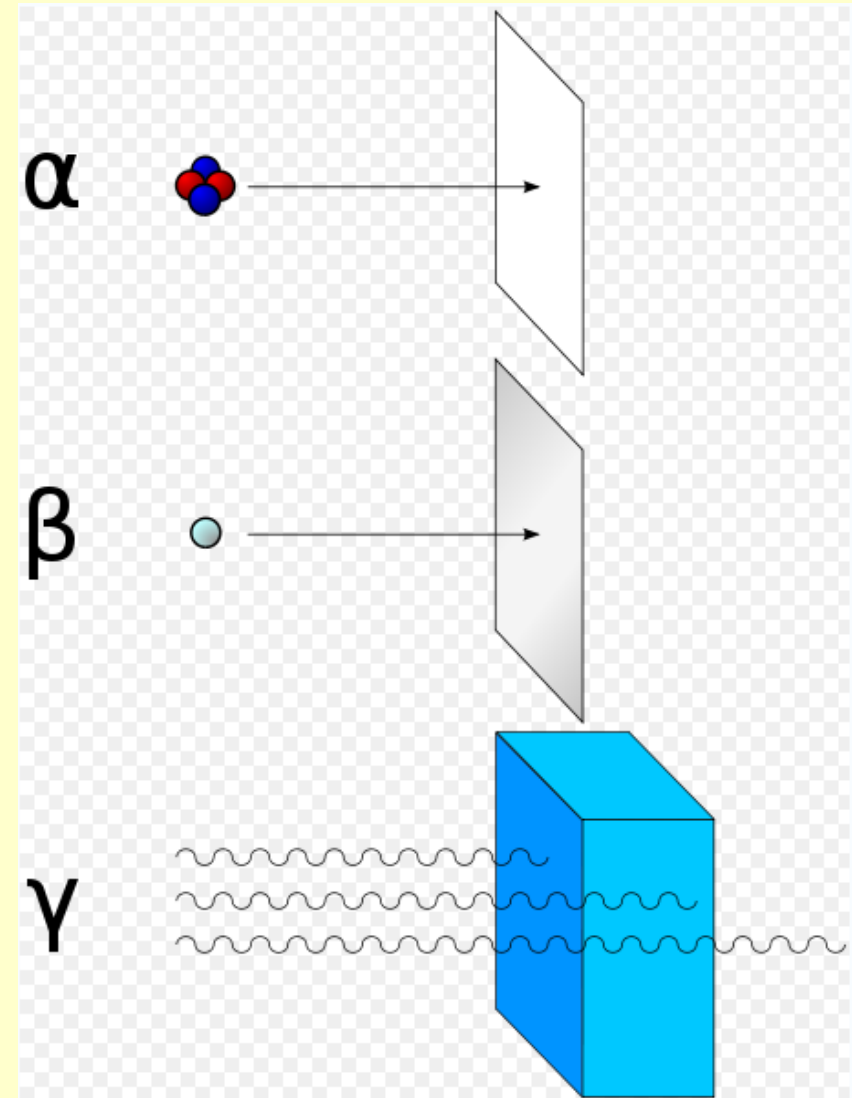
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Three common forms of radioactive decay

Alpha Nucleus of normal He isotope;
2 protons and 2 neutrons (charge = +2).

Beta Electron (charge = -1)

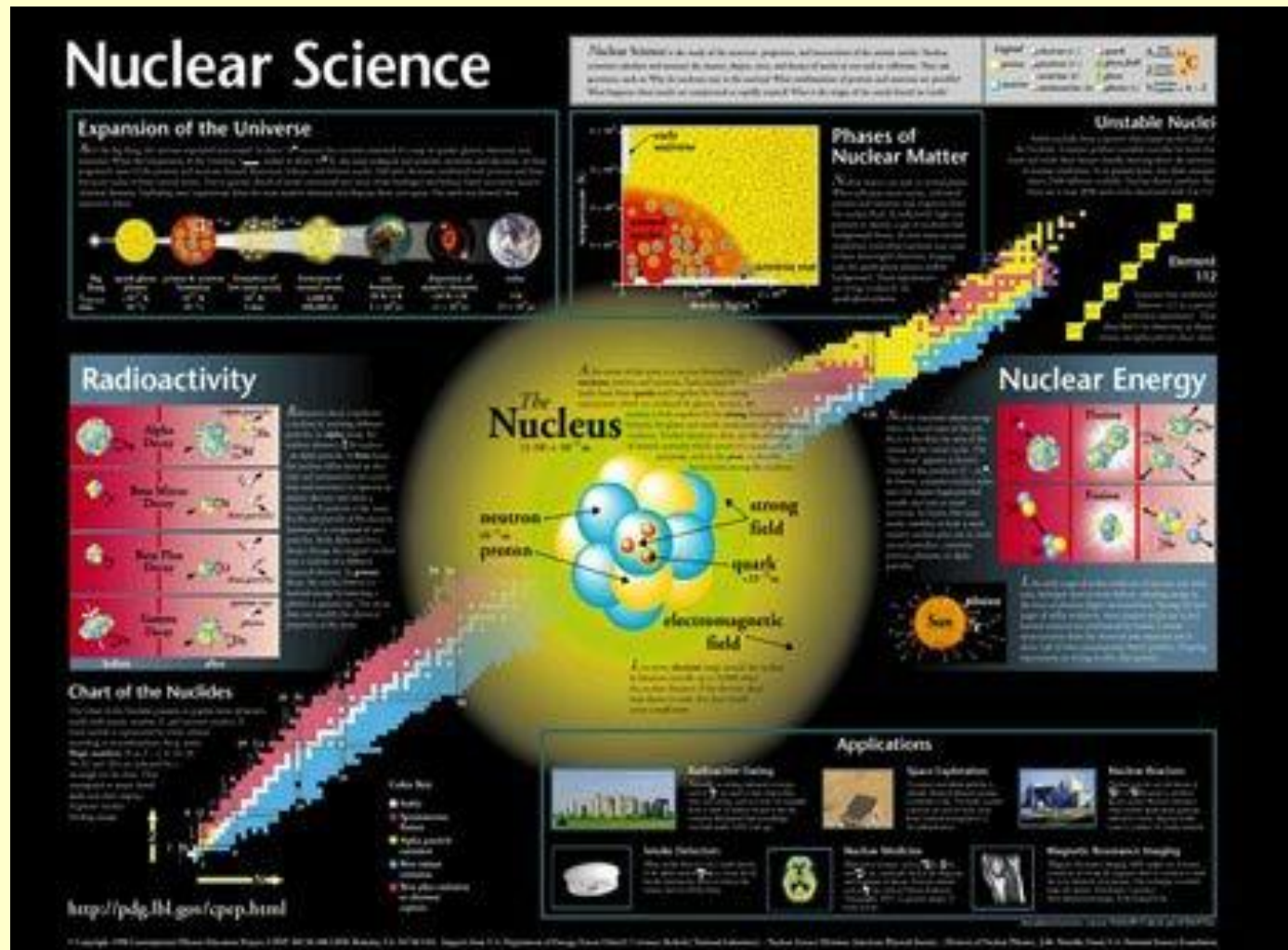
Gamma Photon (particle of light)
called gamma-ray from nucleus,
or x-ray from atom.



Nuclear Science Web Pages

The ABC's of Nuclear Science

<http://www.lbl.gov/abc/>



The Nuclear Science Wall Chart and tour of Nuclear Science

July 18, 2011
BNL/OEP

Modern Physics: Understanding the very small and the very fast.
Brant Johnson, PHENIX@RHIC/Physics Department/BNL

34

The Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics, or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included in this chart because it is one of the fundamental interactions even though not part of the "Standard Model".

FERMIONS

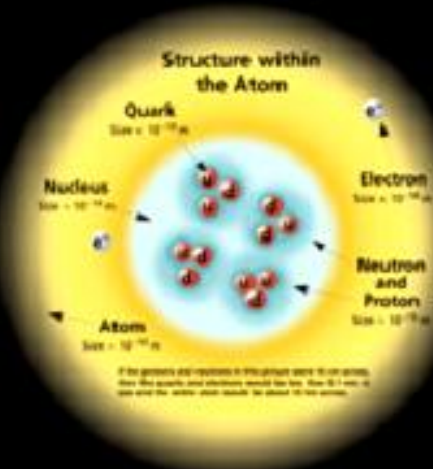
spin = 1/2, 3/2, 5/2, ...

Leptons $g_{\text{spin}} = 1/2$			Quarks $g_{\text{spin}} = 1/2$		
Flavor	Mass GeV/c^2	Electric charge	Flavor	Approx. Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1 \cdot 10^{-6}$	0	u up	0.003	2/3
e^- electron	0.000511	-1	d down	0.006	-1/3
ν_μ muon neutrino	<0.0002	0	c charm	1.3	2/3
μ^- muon	0.106	-1	s strange	0.1	-1/3
ν_τ tau neutrino	<0.02	0	t top	173	2/3
τ^- tau	1.7771	-1	b bottom	4.3	-1/3

^a \hbar is the intrinsic angular momentum of particles. \hbar is given in units of \hbar , which is the quantum unit of angular momentum, where $\hbar = 6.626 \times 10^{-34}$ J s and $\hbar = 1.054 \times 10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In 2 units, the electric charge of the proton is 1.60×10^{-19} coulombs.

The **strong** and, of particle physics, is the electromagnetic (EM), the strong gained its name this time in crossing a potential difference of one volt (**strong**) are given in (eV)² (remember $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$) where $1 \text{ GeV} = 10^9 \text{ eV}$ and $1 \text{ MeV} = 10^6 \text{ eV}$. The mass of the proton is $1.67 \times 10^{-27} \text{ kg}$.



BOSONS

Force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1			Strong Interact spin = 1		
Name	Mass GeV/c ²	Electric Charge	Name	Mass GeV/c ²	Electric Charge
γ photon	0	0	g gluon	0	0
W^-	80.4	-1			
W^+	80.4	+1			
Z^0	91.187	0			

Likely charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and e^+ and e^- interact have no strong interactions, and hence no color charge.

Quarks Confined in Mesons and Baryons

This process, where quarks and gluons, the constituents of some matter particles, called **hadrons**, this confinement, involving results from multiple exchanges of gluons among the color-charged constituents, as color-charged particles squarish and gluons flow apart. We are in the color flow field between them increases. The energy eventually is converted into additional quark-antiquark pairs like those below. The quarks and antiquarks then combine into hadrons, these are the particles seen to emerge. Two types of hadrons have been observed in nature, www.aps.org and www.feynman.org.

Worldwide Shipping Index available

The strong binding of color-charged proteins and nucleic acids back to the α helical strong interactions between their color-charged constituents. It is useful to the reader who find interactions that bind nucleic acids to the α helical. It can also be found in the exchange of nucleic acids between the helices.

PROPERTIES OF THE INTERACTIONS

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$					
Baryons are fermions (half-integers)					
There are about 100 types of Baryons.					
Symbol	Name	Quark content	Electric charge	Mass (MeV)	Spin
p	proton	uud	1	938.27	$\frac{1}{2}$
\bar{p}	anti-proton	$\bar{u}\bar{u}\bar{d}$	-1	938.27	$\frac{1}{2}$
n	neutron	udd	0	939.56	$\frac{1}{2}$
\bar{n}	anti-neutron	$\bar{u}\bar{d}\bar{d}$	0	939.56	$\frac{1}{2}$
Λ^0	lambda	uds	0	1115.68	$\frac{1}{2}$
Λ^+	lambda	uus	1	1115.68	$\frac{1}{2}$

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic	Strong
Acts on:	Matter – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, leptons	Electrically charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength relative to electromagnetism (10^{-16}) as for two e- quarks at (10^{-16}) m	10^{-41}	0.8	1	25
	10^{-41}	10^{-4}	1	60
Can force protons to fuse	10^{-36}	10^{-2}	1	Not applicable to leptons
				30

[illegible]

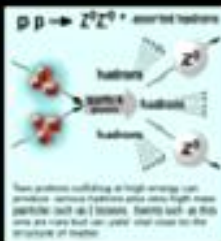
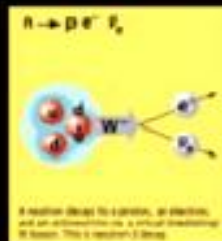
Method and Assumptions

For every particle type, there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless χ or $\bar{\chi}$ change is desired).

Partners and antipartners have identical mass, and are fed opposite charges, some electrically neutral bosons (e.g., Z^0), and W^+ and W^- , but not W^0 or W^1 are these same antipartners.

Fragebogen

These diagrams are an abstract representation of physical processes. They are not meant to represent any meaningful picture. Green shaded areas represent the cloud of plasma in the quark field, and red lines the quark paths.



The Particular Advantages

Visit the award-winning web feature The Perfect Automobile at <http://www.ford.com>. Get your perfect automobile listed.

Supplemental materials

This report has been made possible by the generous support of
a U.S. Department of Energy
Advanced Learning Research Laboratory
Advanced Learning Laboratory, Center
for the Study of Learning, University of Wisconsin, Madison, WI 53706

EXPLANATION

©1996-1998, Copyright by Physics Education Project (PEP), a non-profit organization for teachers, professors, and students. Send requests to: PEP, MS 98, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720. For information go to: <http://www.berkeley.edu/pep>

<http://pdg.lbl.gov/cpeg.html>

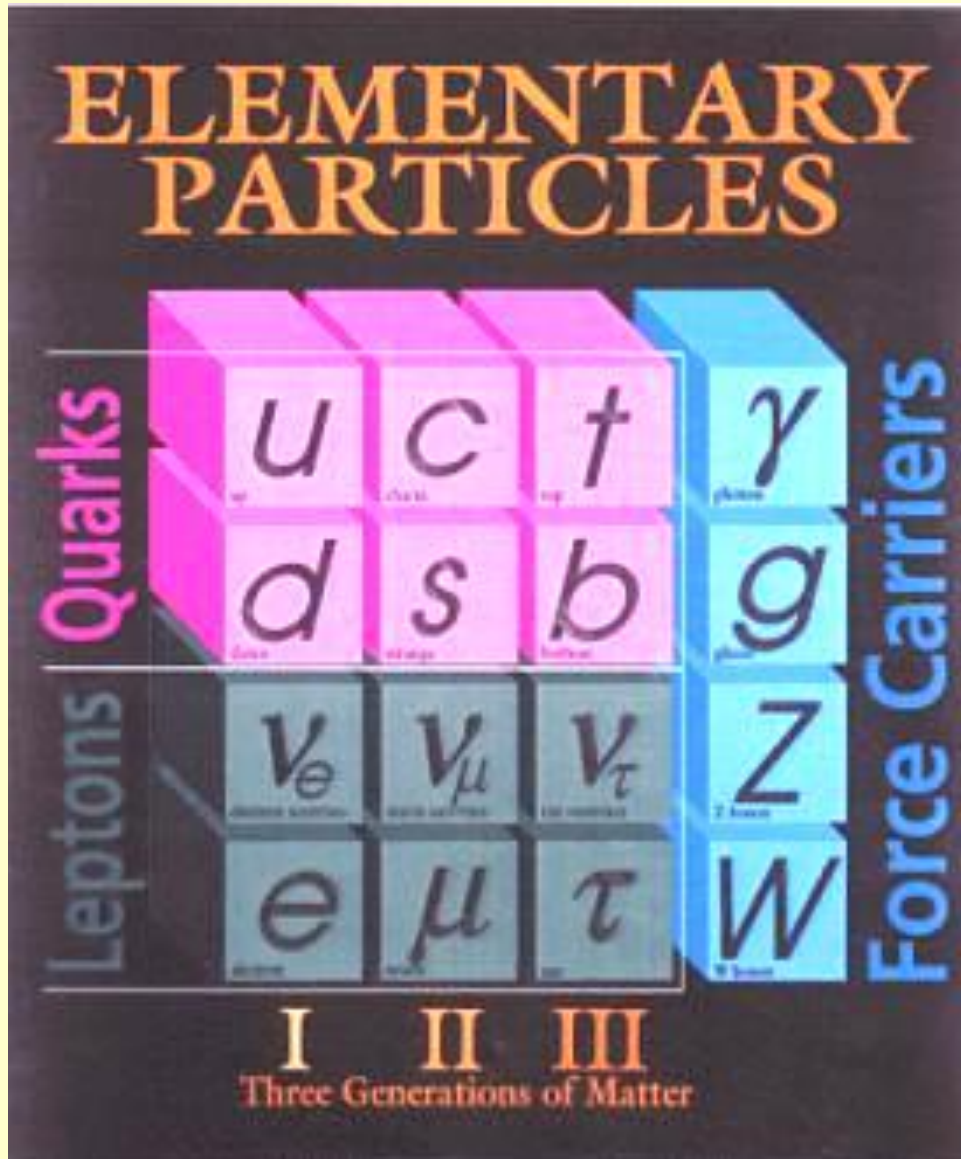
<http://particleadventure.org/particleadventure/> <http://www.cpepweb.org/particles.html>

July 18, 2011
BNL/OEP

Modern Physics: Understanding the very small and the very fast.
Brant Johnson, PHENIX@RHIC/Physics Department/BNL

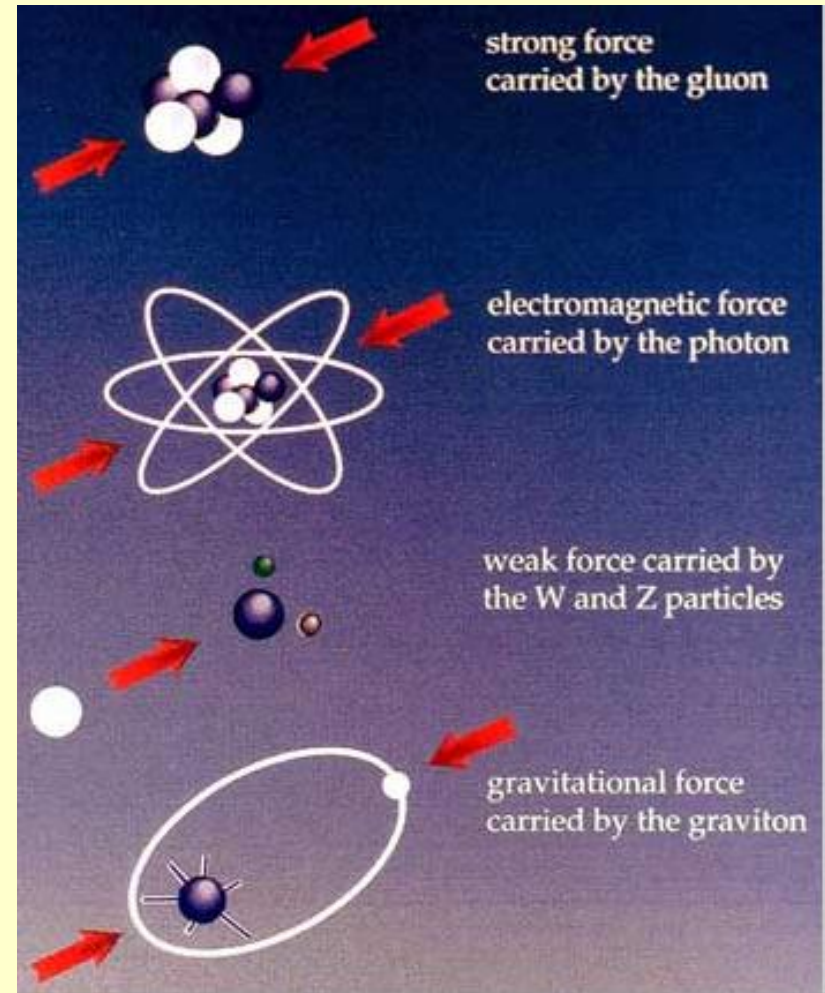
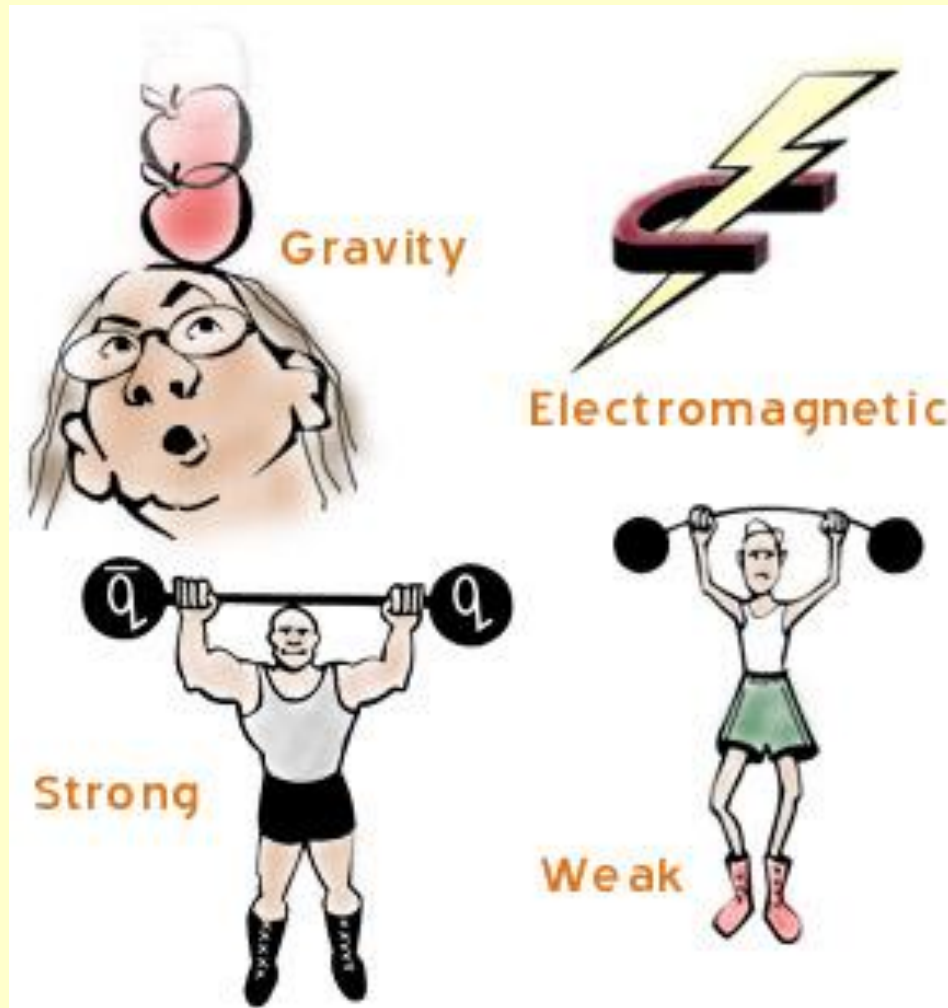
35

Particles and Fields



Matter particles		
QUARKS	up	u
	down	d
	charm	c
	strange	s
	top	t
	bottom	b
LEPTONS	electron neutrino	ν_e
	electron	e
	muon neutrino	ν_μ
	muon	μ
	tau neutrino	ν_τ
	tau	τ
Force carriers		
the photon	γ	
vector bosons	W^+, W^-, Z^0	
gluons (8)	g	

Four Fundamental Interactions

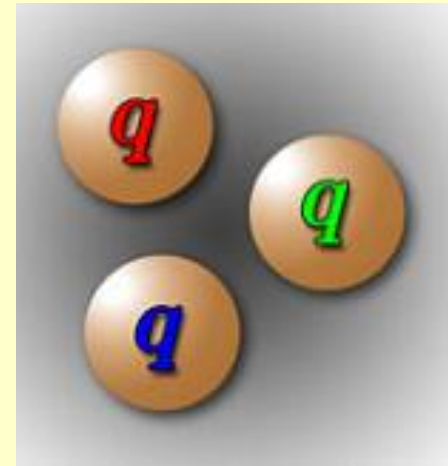


<http://particleadventure.org/particleadventure/>

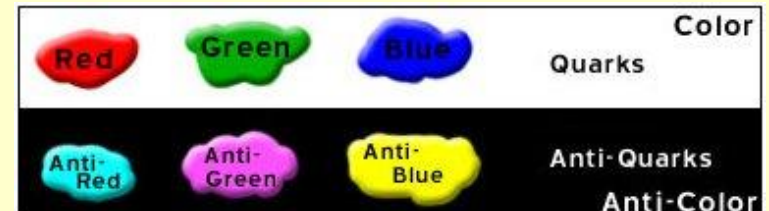
Baryons (protons, neutrons, etc.)

Sample Fermionic Hadrons Baryons (qqq) and Anti-baryon ($\bar{q}\bar{q}\bar{q}$)

Symbol	Name	Quark Content	Electric Charge	Mass (GeV/c^2)	Spin
p	proton	uud	+1	0.938	1/2
\bar{p}	anti-proton	$\bar{u}\bar{u}\bar{d}$	-1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	-1	1.672	3/2



Color neutral



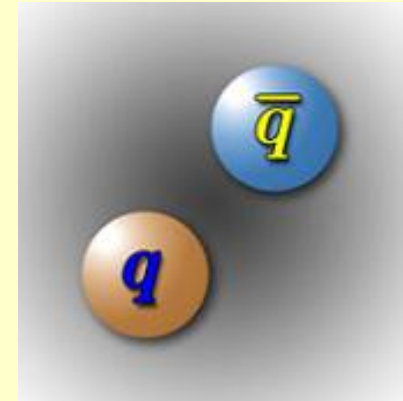
Color neutral

Meson (pions, kaons, etc.)

Sample Bosonic Hadrons Mesons ($q\bar{q}$)

Symbol	Name	Quark Content	Electric Charge	Mass (GeV/c ²)	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	-1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
D^+	D+	$c\bar{d}$	+1	1.869	0
η_c	eta-c	$c\bar{c}$	0	2.979	0

Color neutral



Quarks carry a color



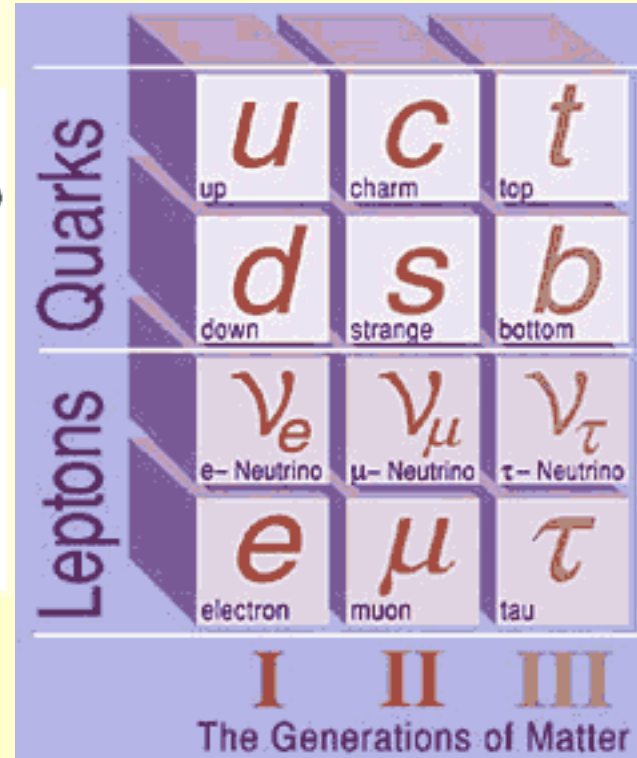
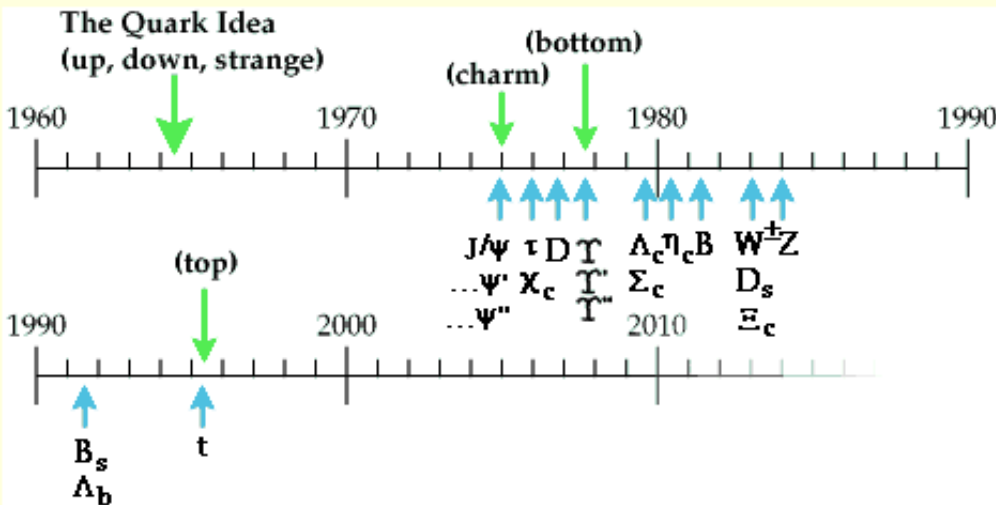
Anti-quarks carry an anti-color



Gluons carry a color and an anti-color

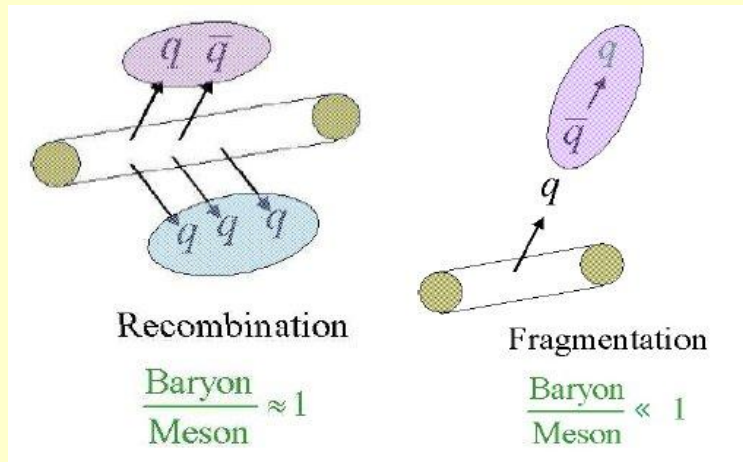
Standard Model: Leptons, Quarks, and Gluons

Particles discovered 1964 - present:

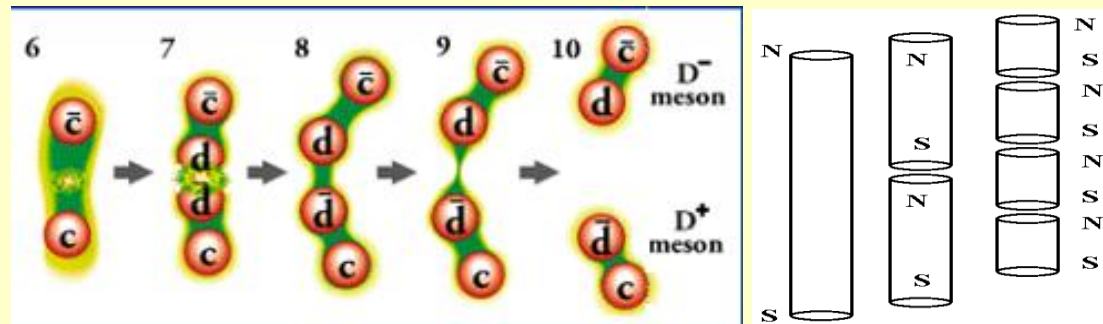


Mesons ($q\bar{q}$) Pion (π) kaon (K), J/ψ, φ, ω

Baryons (qqq) and Anti-baryon ($\bar{q}\bar{q}\bar{q}$) p, n, Λ, ...



Cannot separate quarks (or poles of magnets)



Inside the RHIC tunnel



Relativistic Heavy Ion Collider

Relativistic:

Something traveling at nearly the speed of light

Heavy Ion:

Typically fully-stripped gold ions (bare gold nuclei)

Collider:

Two ion beams aimed at each other to hit head-on.

RHIC by the numbers:

Circumference 3.83 km = 2.38 miles

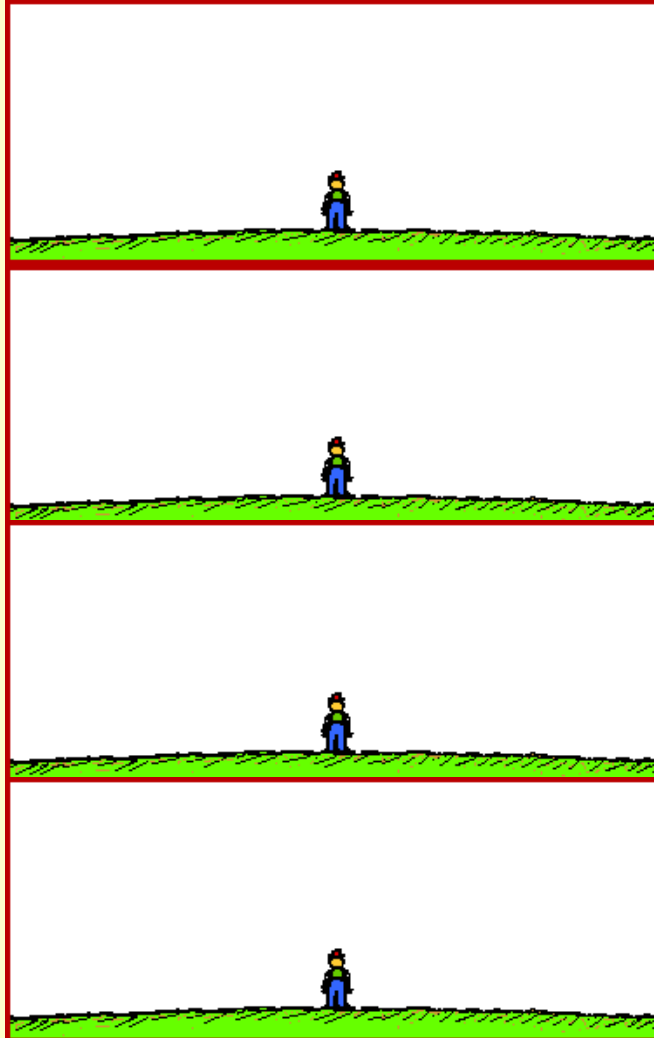
***Maximum energies 100+100 GeV heavy ions,
250+250 GeV protons***

Circulation frequency 80,000/sec (80 kHz)

Collision frequency (x100) 8 Mhz

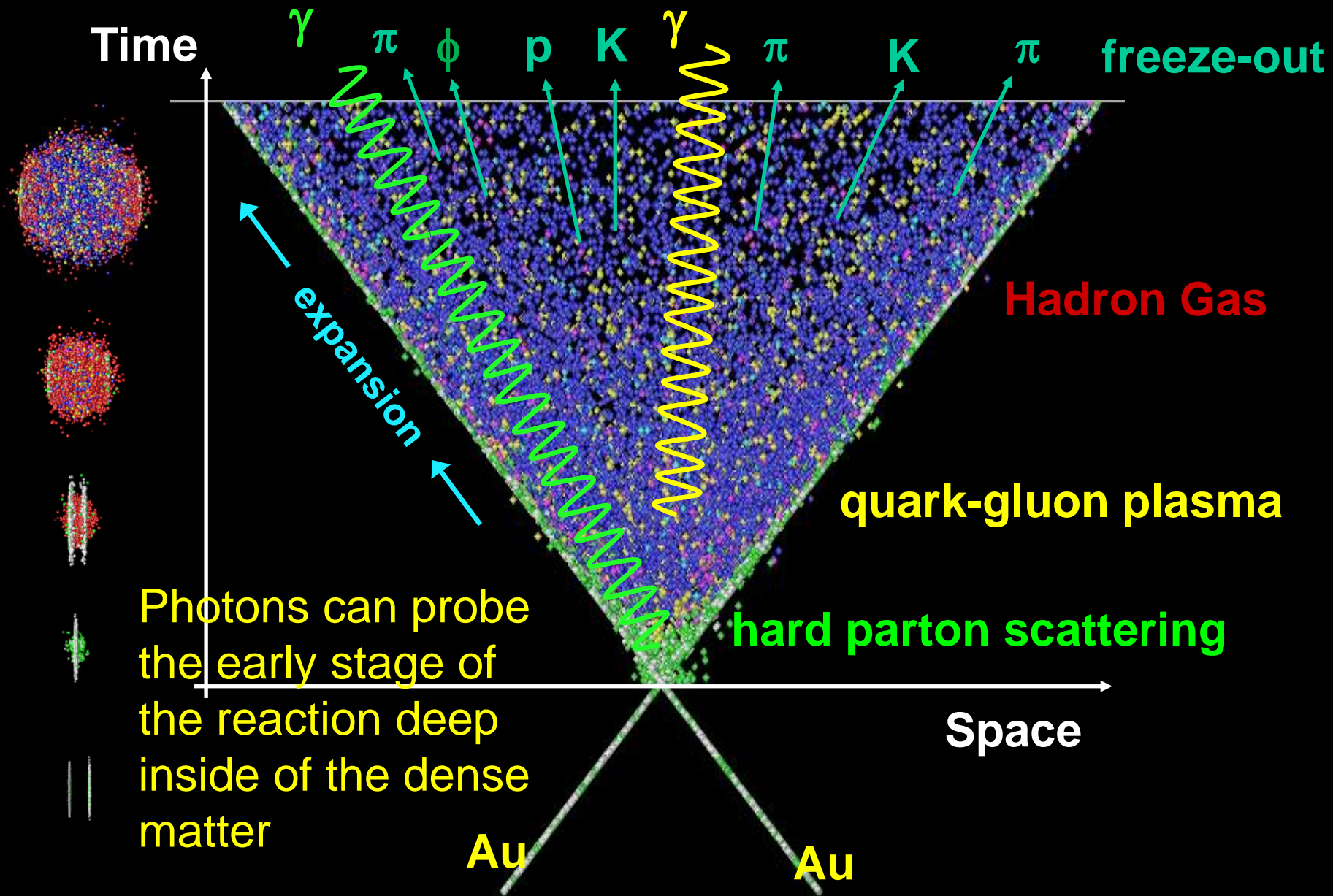
Ion velocity 99.9995% speed of light.

Relativistic Length Contraction

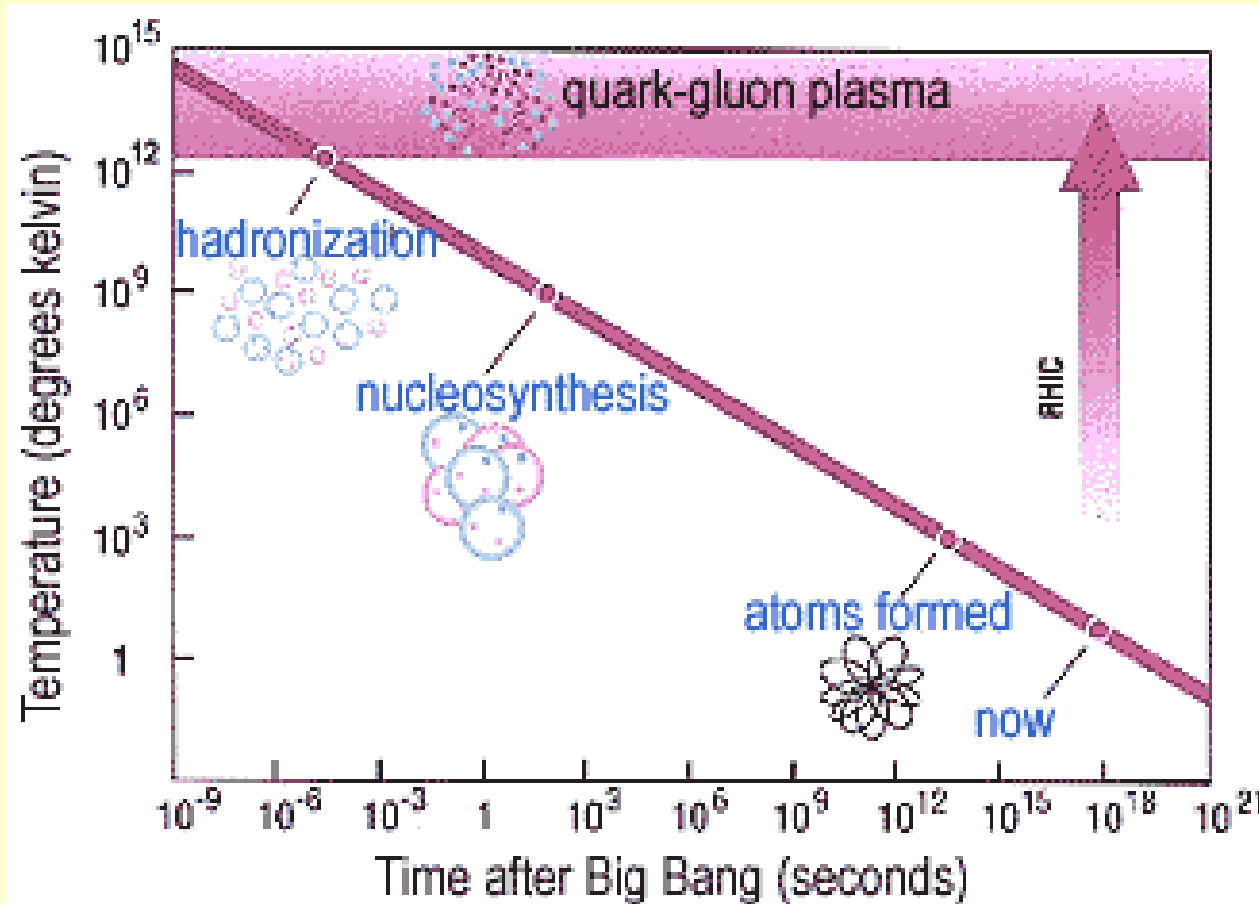


Speed of Spaceship	Observed Length	Observed Height
At rest	200 ft	40 ft
10 % the speed of light	199 ft	40 ft
86.5 % the speed of light	100 ft	40 ft
99 % the speed of light	28 ft	40 ft
99.99 % the speed of light	3 ft	40 ft

Photon Probe of Nuclear Collisions

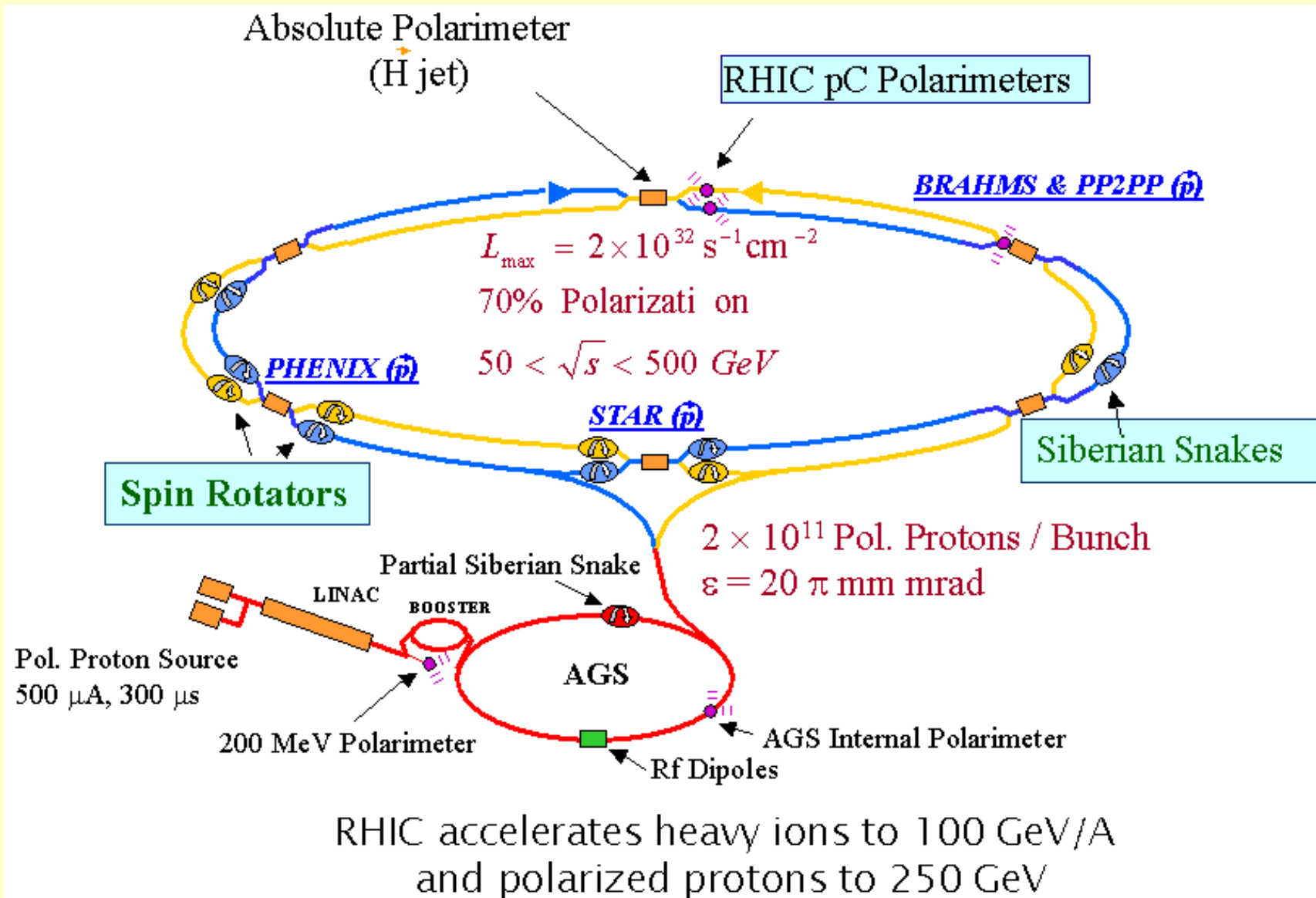


RHIC As A Time Machine

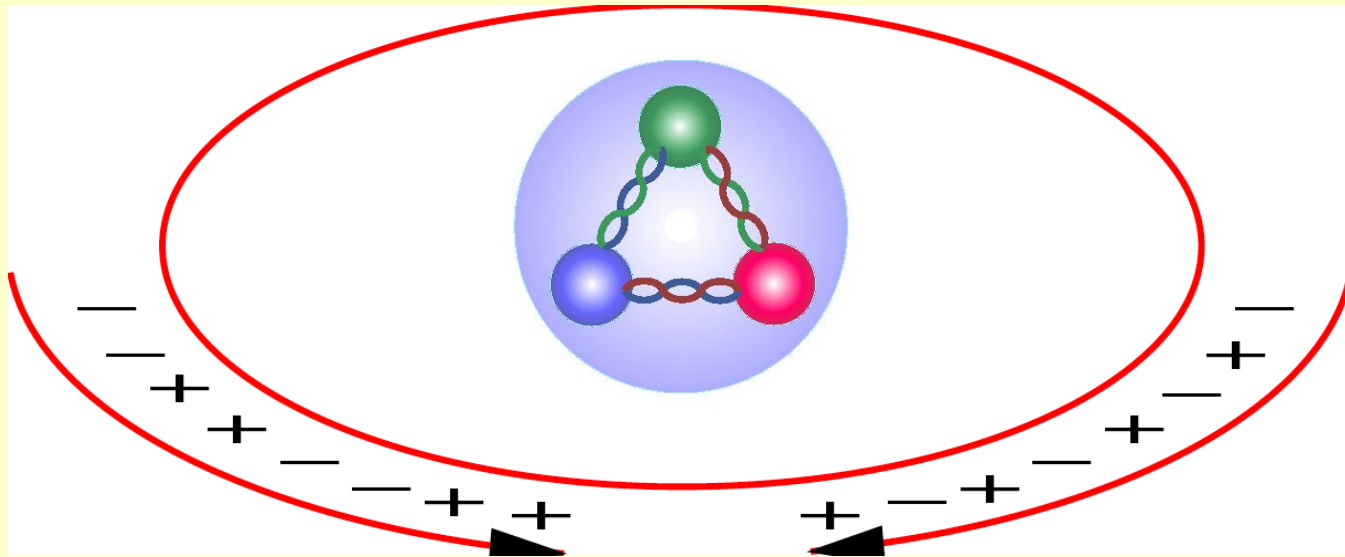


- Temperature of collisions is about 4 trillion degrees
500,000 times hotter than the center of the sun!
- Super-high temperatures reminiscent of early universe!

RHIC is World's first (and only) polarized proton collider



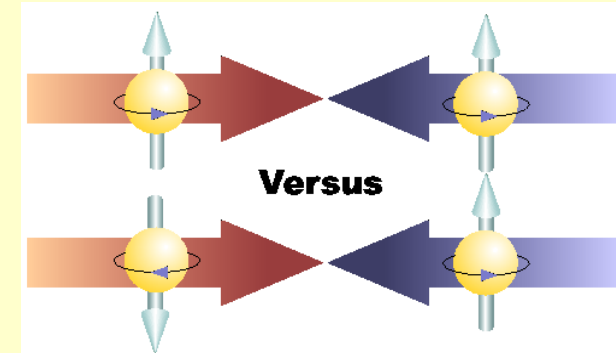
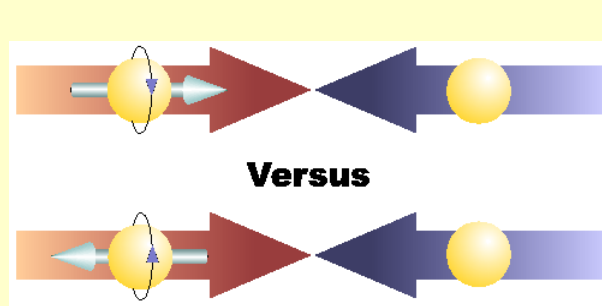
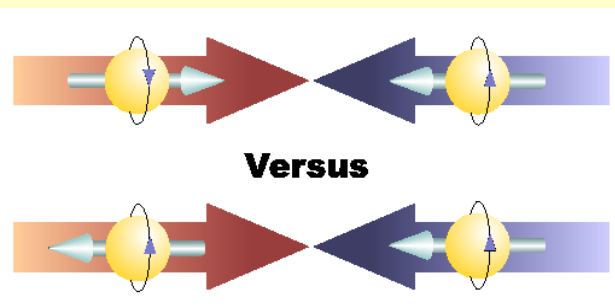
Spin Physics (measure spin substructure)



$$A_{LL} \rightarrow \frac{\Delta G}{G}$$

$$A_L^{W^\pm} \rightarrow \frac{\Delta q}{q}; \frac{\Delta \bar{q}}{\bar{q}}$$

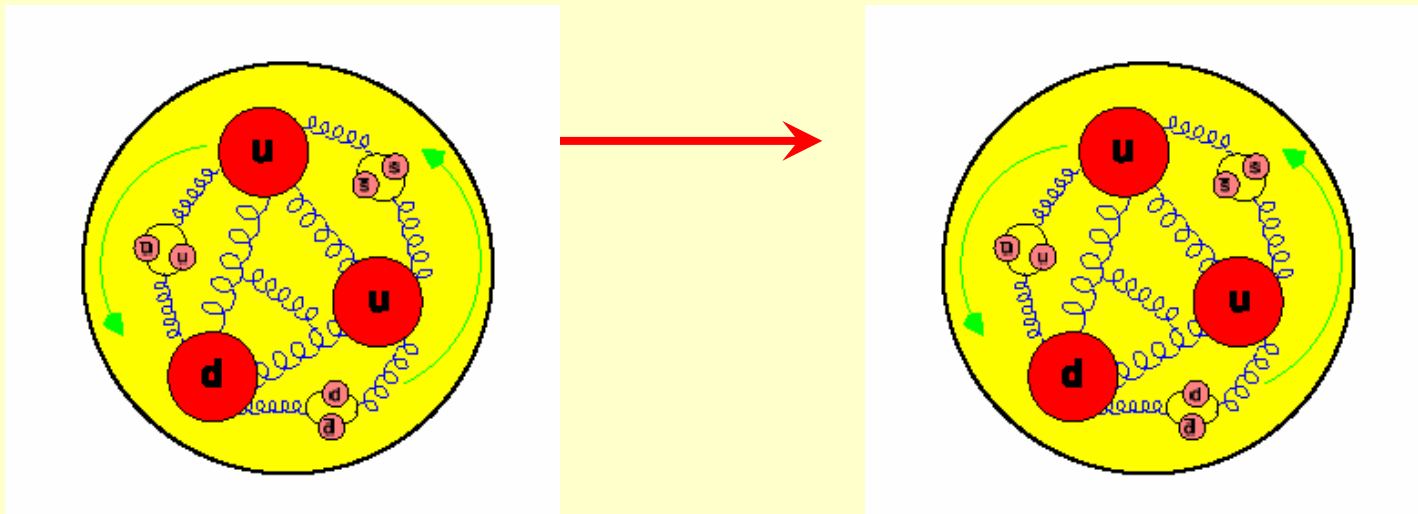
$$A_N, A_{TT}$$



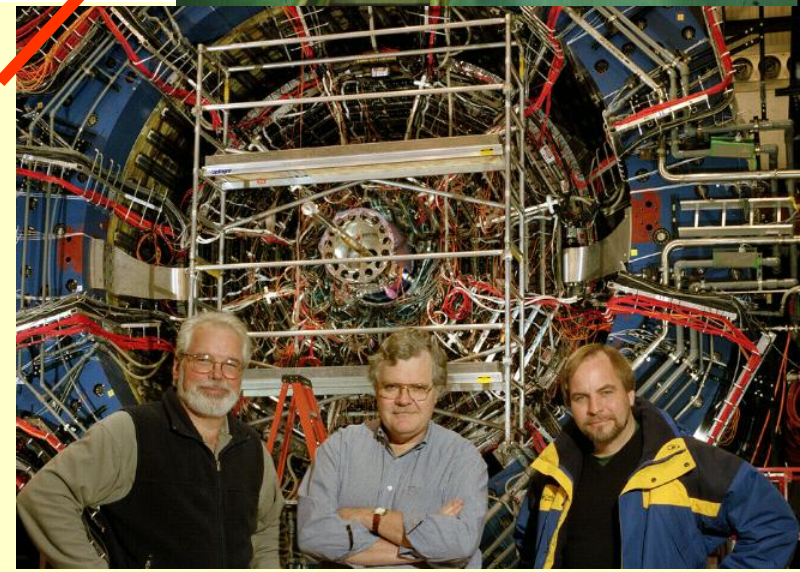
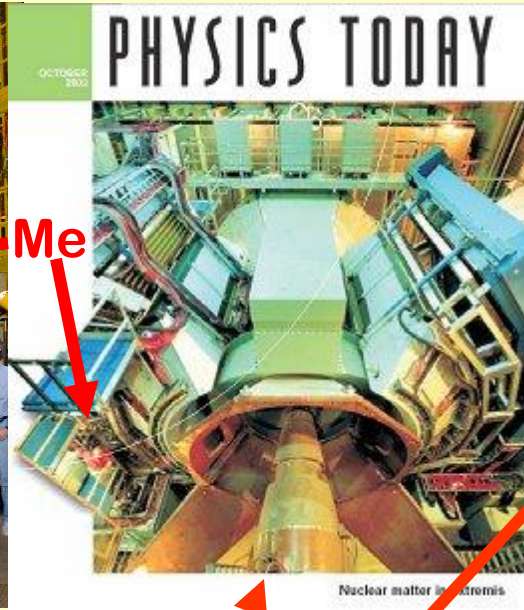
Studying Proton Structure with Quark and Gluon Probes

$$\frac{1}{2} = \frac{1}{2} \cdot \Delta\Sigma + \Delta G + L_{G+q}$$

At ultra-relativistic energies the proton represents a jet of quark and gluon probes



PHENIX, STAR, (formerly PHOBOS, BRAHMS)



Me

PHENIX

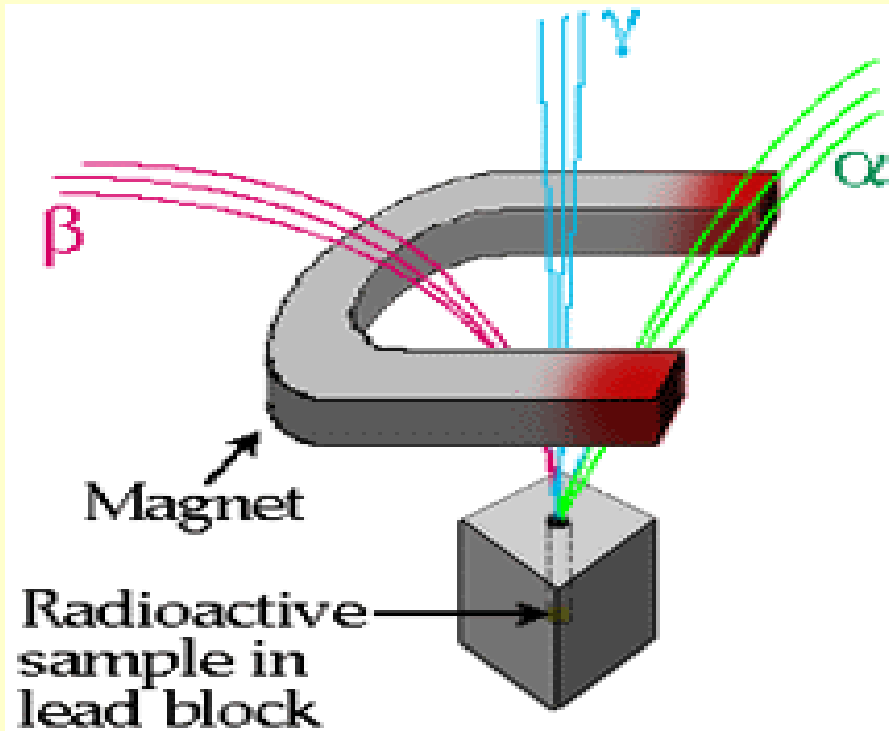
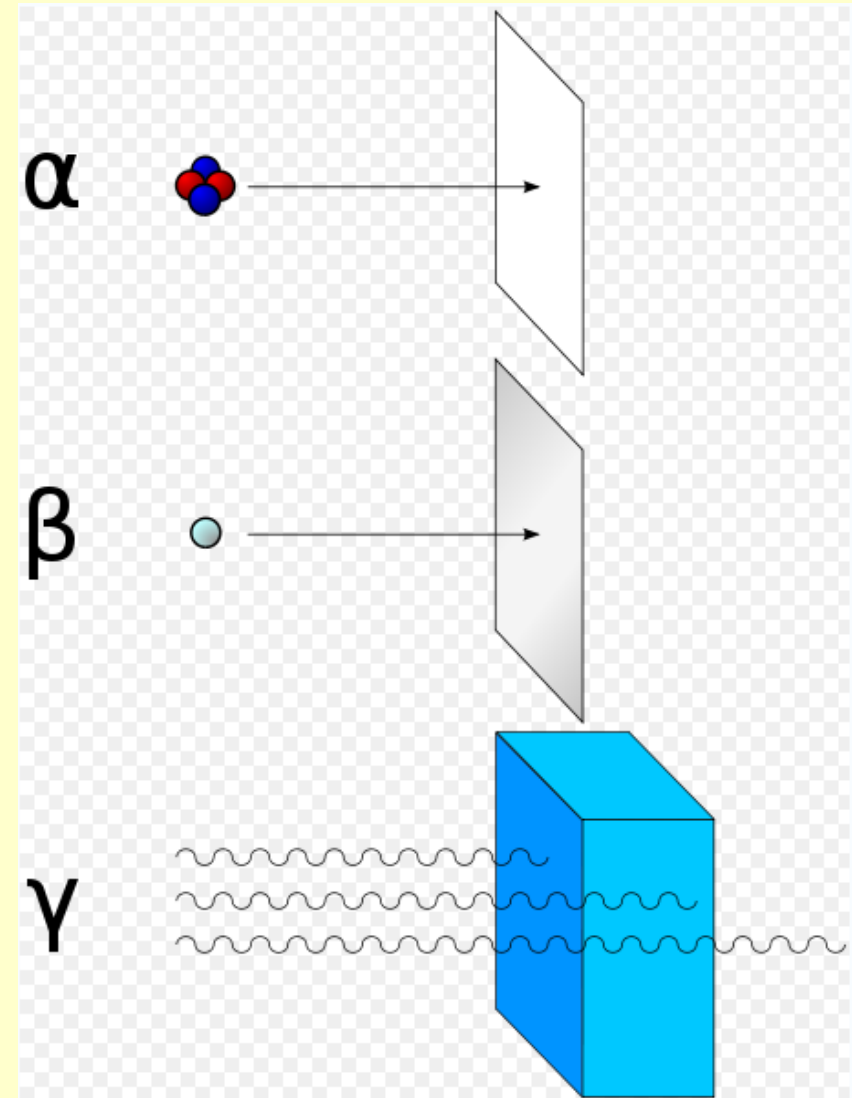
STAR

Three common forms of radioactive decay

Alpha Nucleus of normal He isotope;
2 protons and 2 neutrons (charge = +2).

Beta Electron (charge = -1)

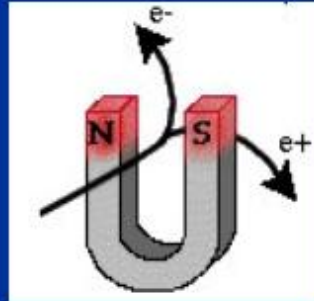
Gamma Photon (particle of light)
called gamma-ray from nucleus,
or x-ray from atom.



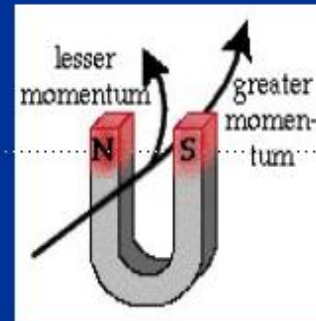
Tracking Detectors Measure Charge and Momentum



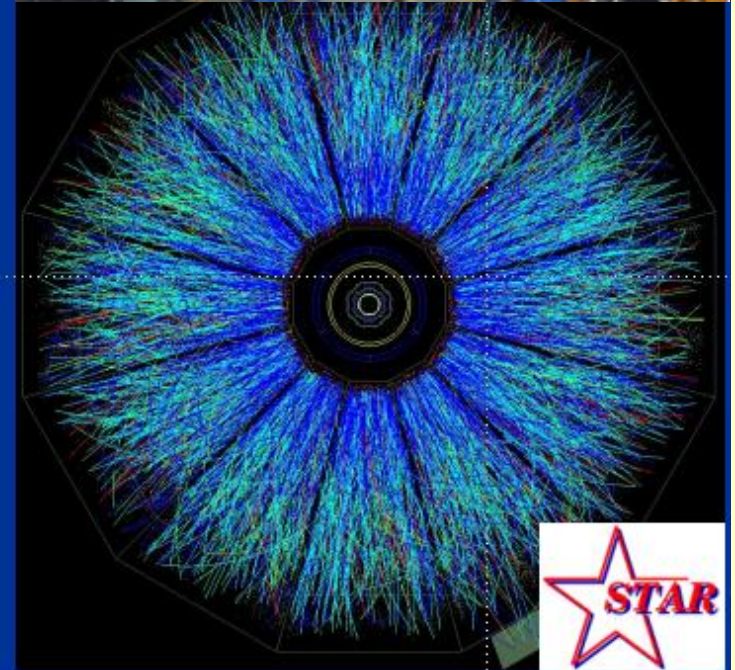
*Event
Displays*



*Left/Right
tells charge*

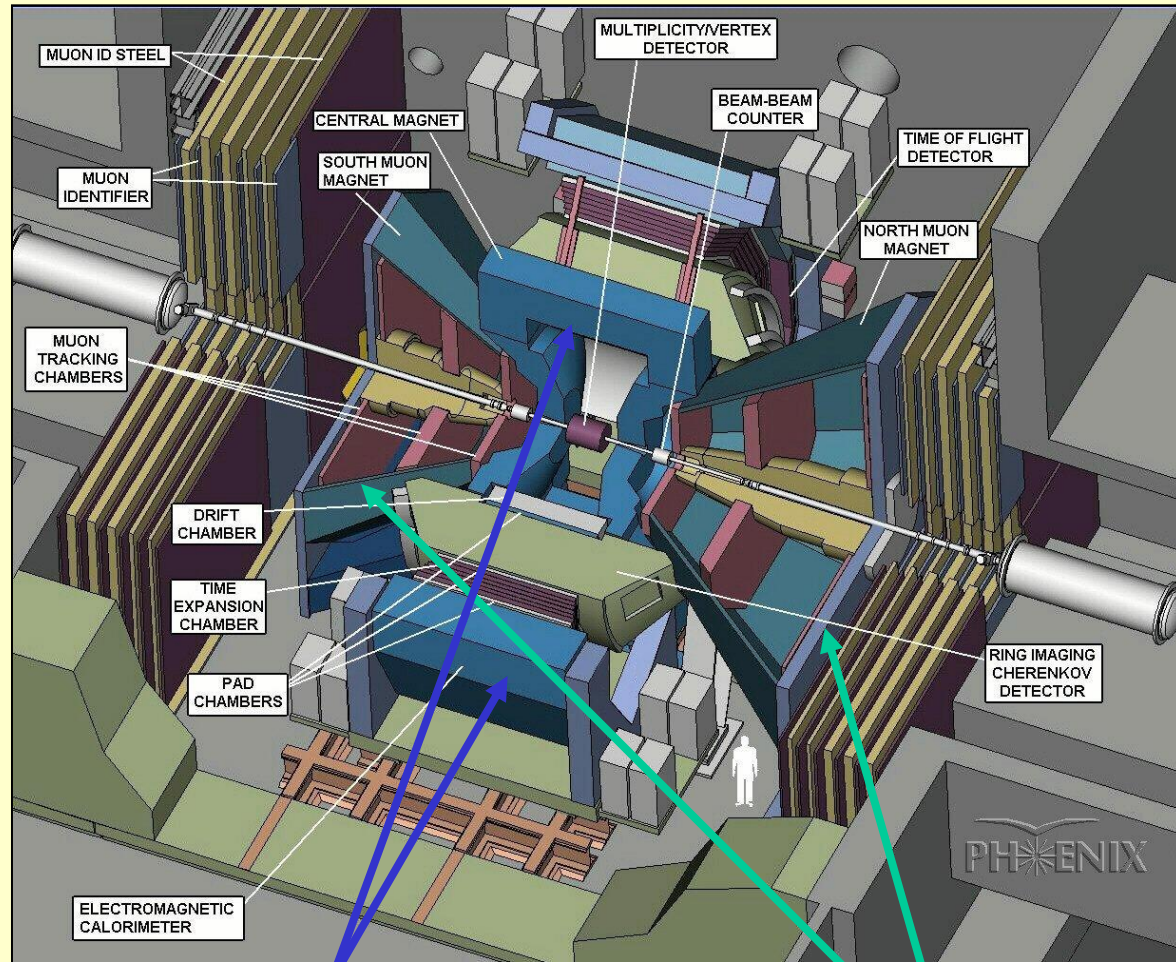


*Curvature is
proportional
to $1/p$*



The PHENIX Detector at RHIC

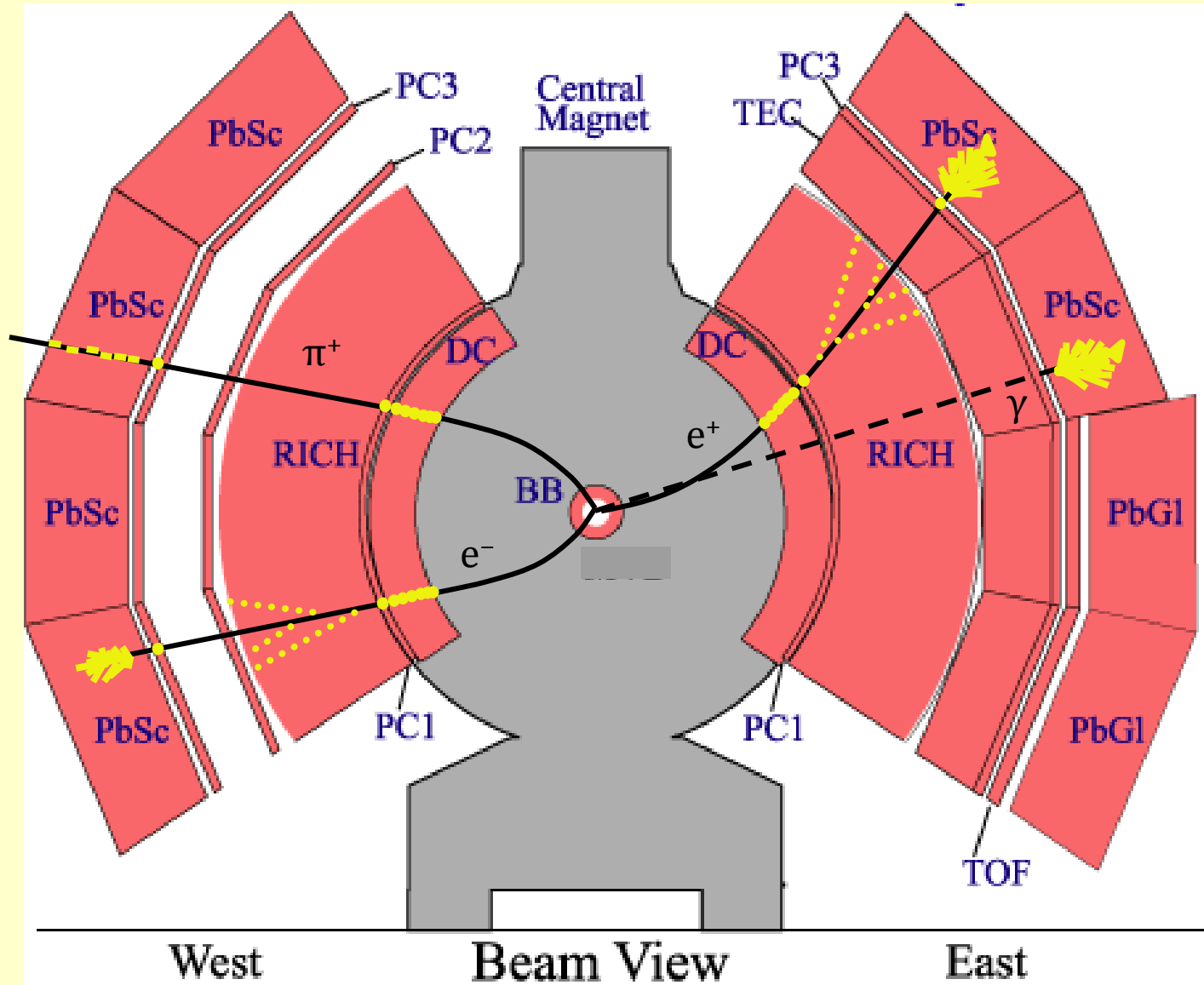
- Two Central Arm Spectrometers to measure hadrons, electrons, photons
- Two Forward Spectrometers to measure muons
- All four used to identify particle type; measure momentum.



two central electron/photon/hadron spectrometers

two forward muon spectrometers

PHENIX: Tracking & Particle Identification



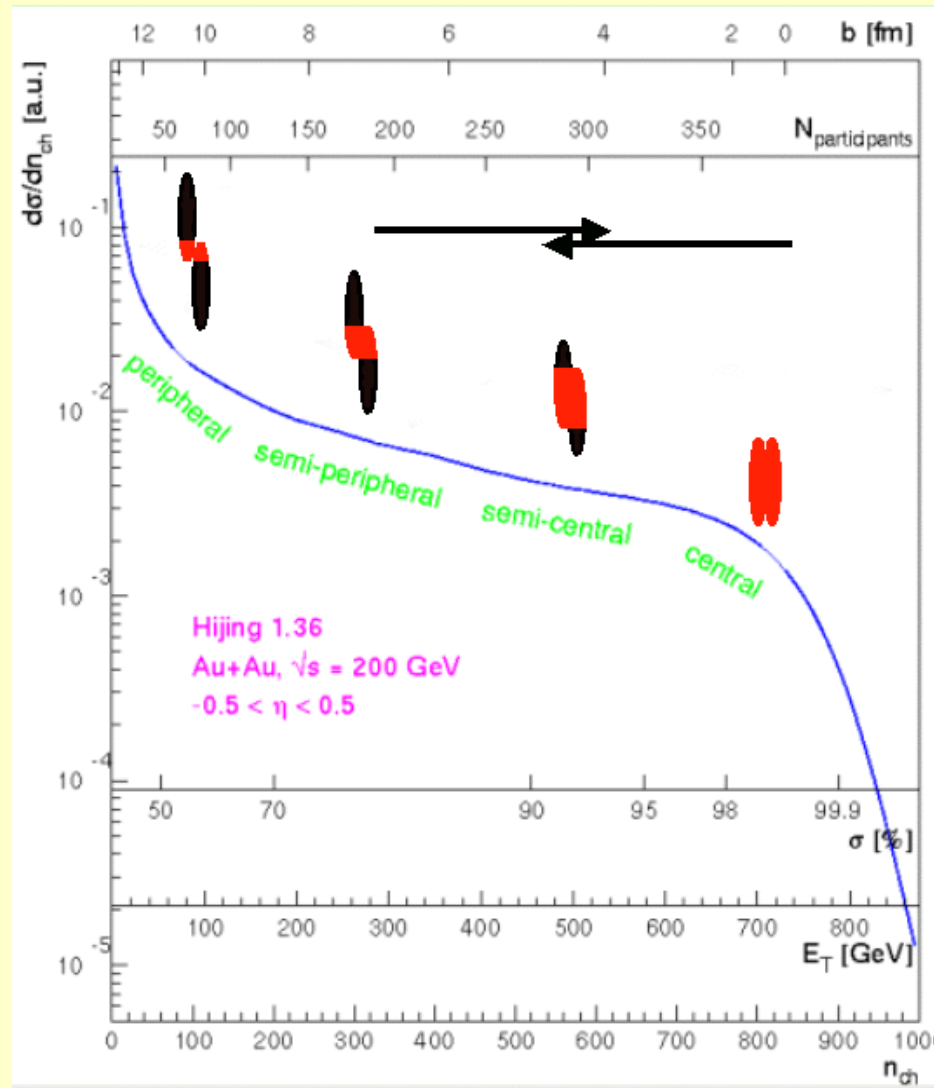
Multiplicity, Centrality, Peripheral, Central

Multiplicity:

A large number or wide range (of something).



**At RHIC:
the something
is particles**

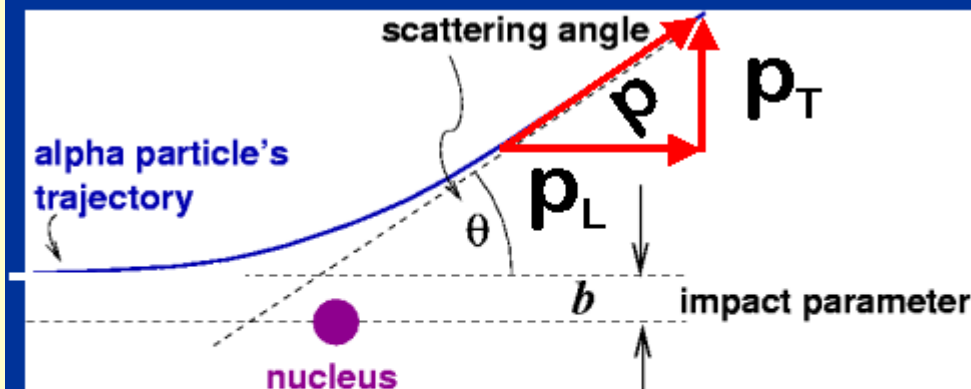


Centrality:

The state of being central; tendency towards a center.

RHIC collisions :
peripheral
semi-peripheral
semi-central
most central

Soft and Hard Scattering: What happens at high p_T ?



↑ Transverse Momentum

p_T

→ Longitudinal Momentum

Soft Scattering:

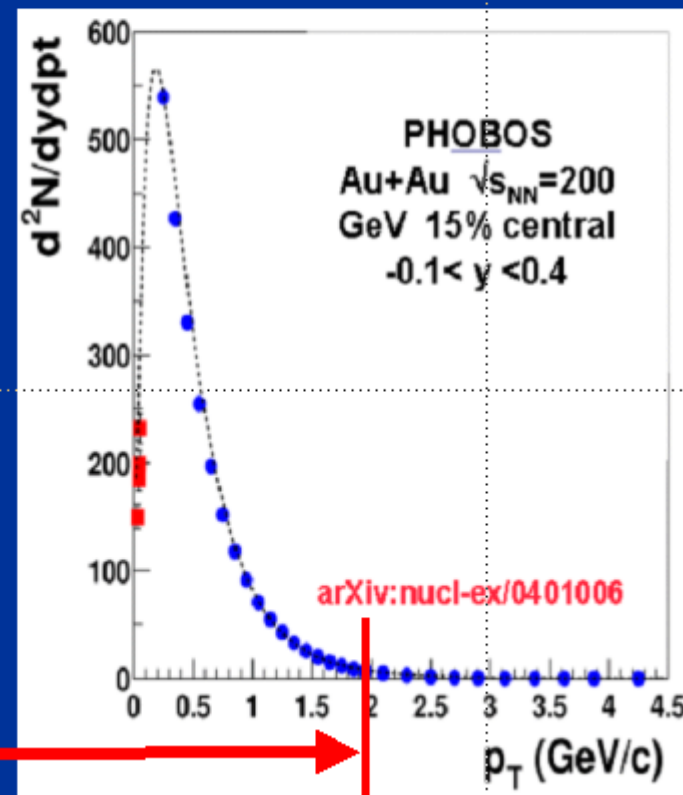
Low p_T like in plum pudding model prediction.

Hard Scattering:

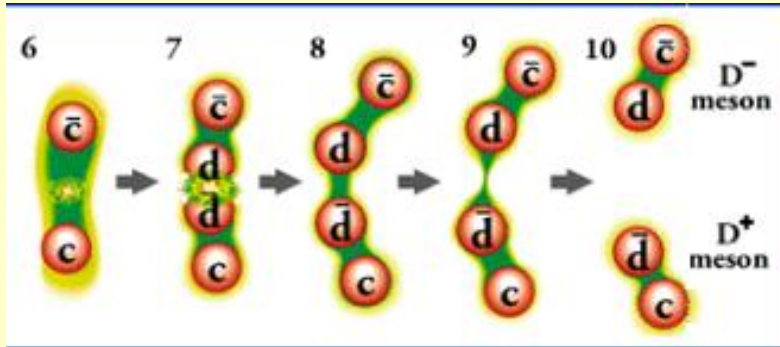
High p_T , like in Rutherford scattering results.

⇒ Hard scattering implies substructure

Most particles Produced at RHIC are "Soft" (Low p_T)

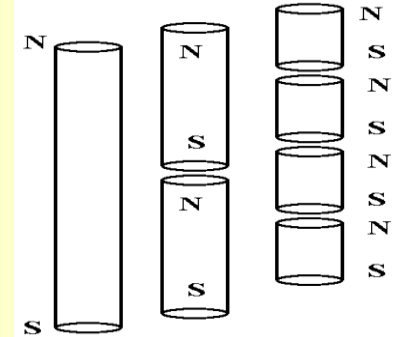


2004 Nobel Prize in Physics: Asymptotic Freedom (1973)



Cannot separate quarks

Cannot separate N and S poles



<http://www.physicstoday.org/vol-57/iss-10/nobel.html>

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2004 jointly to

David J. Gross

Kavli Institute for Theoretical Physics, University of California
Santa Barbara, CA, USA



H. David Politzer

H. David Politzer

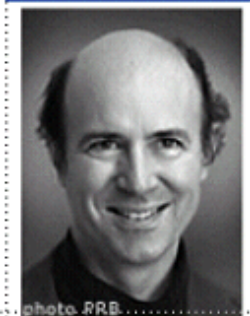
California Institute of Technology
Pasadena, CA, USA

Frank Wilczek

Massachusetts Institute of Technology (MIT)
Cambridge, MA, USA



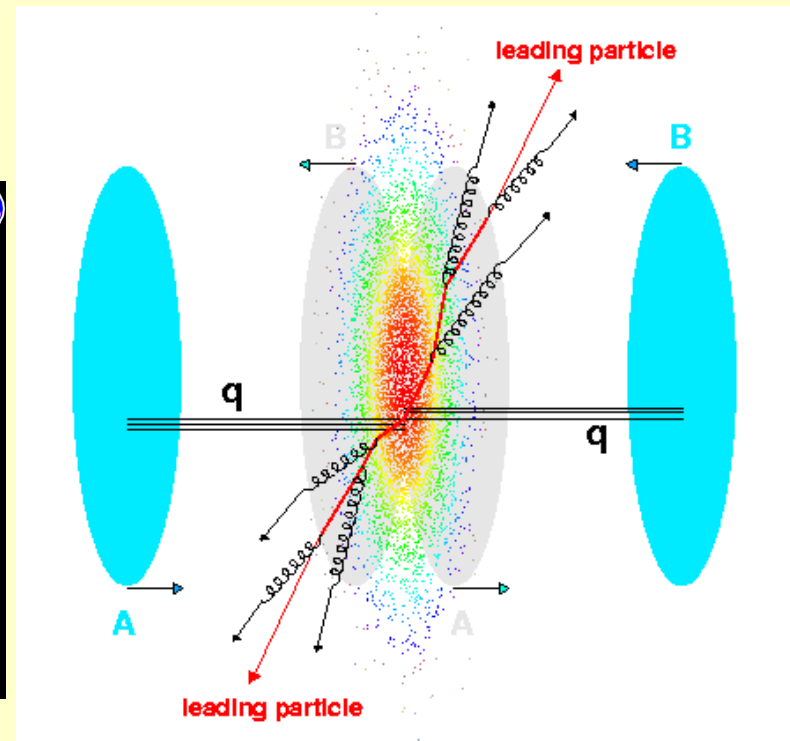
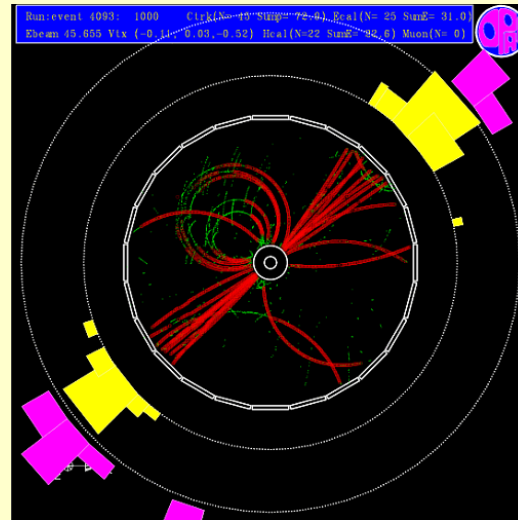
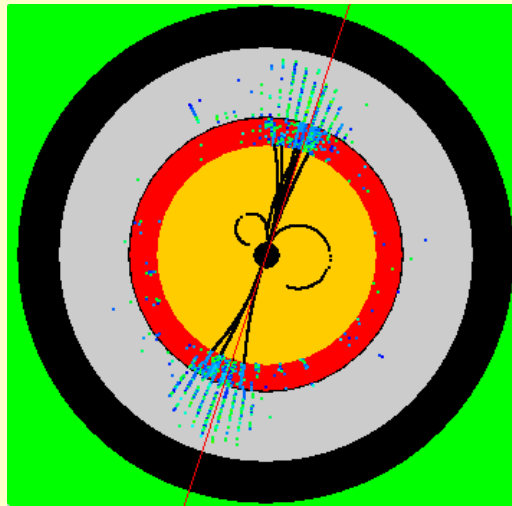
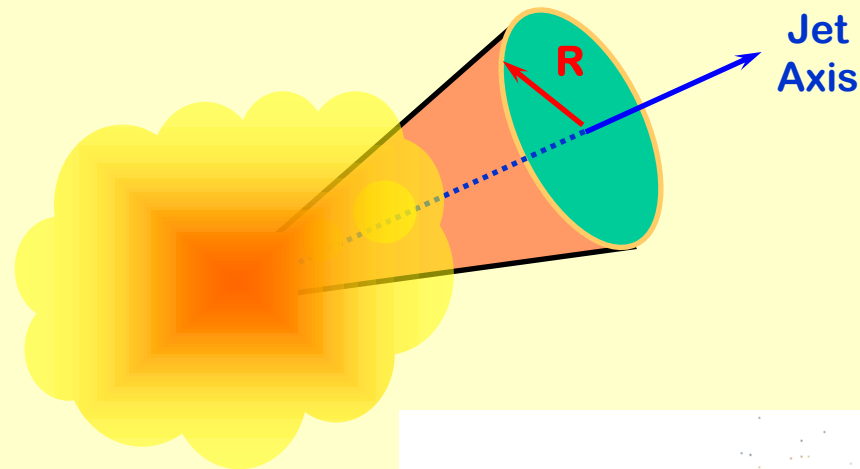
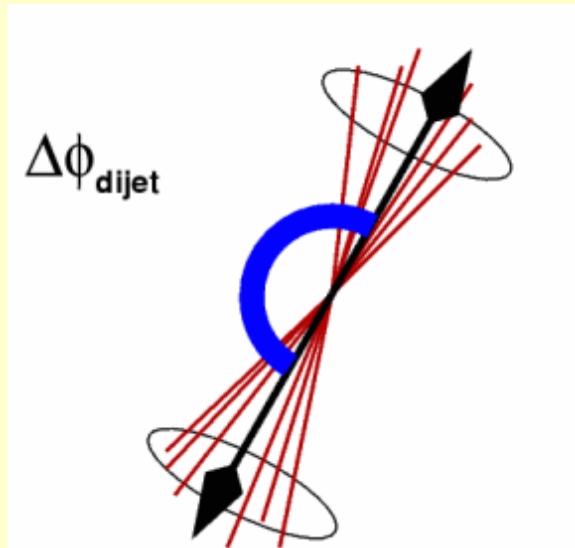
David J. Gross



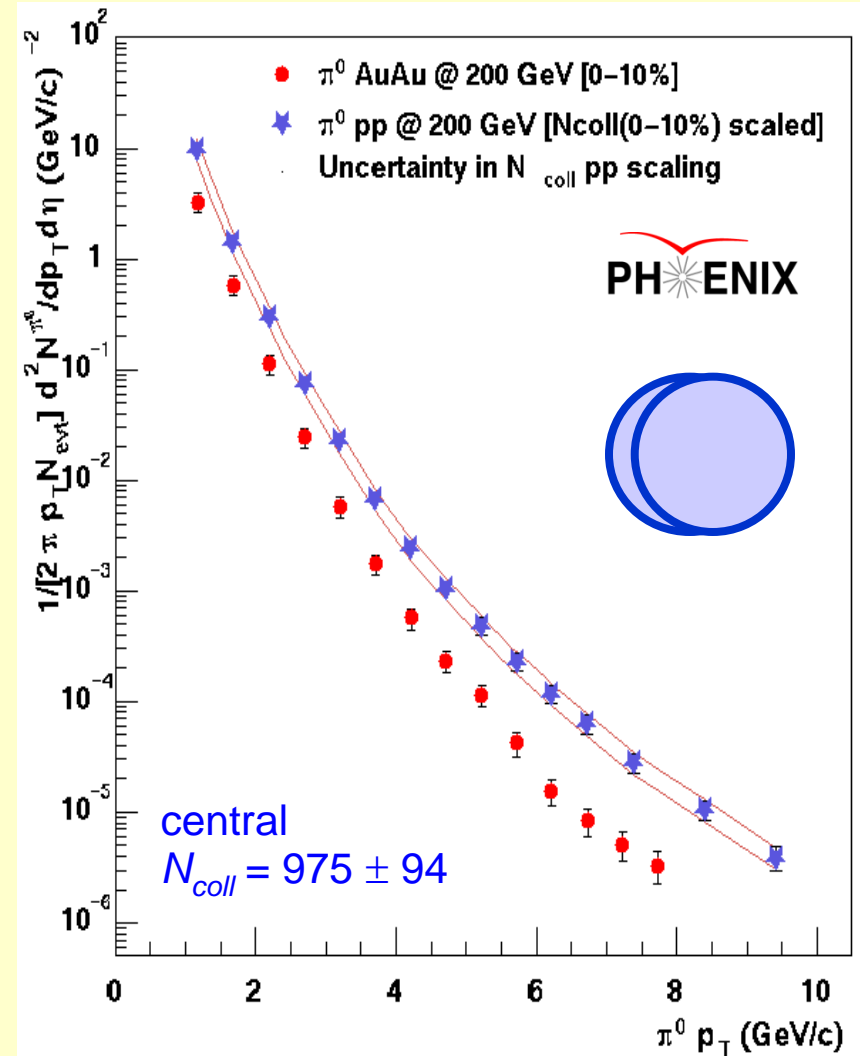
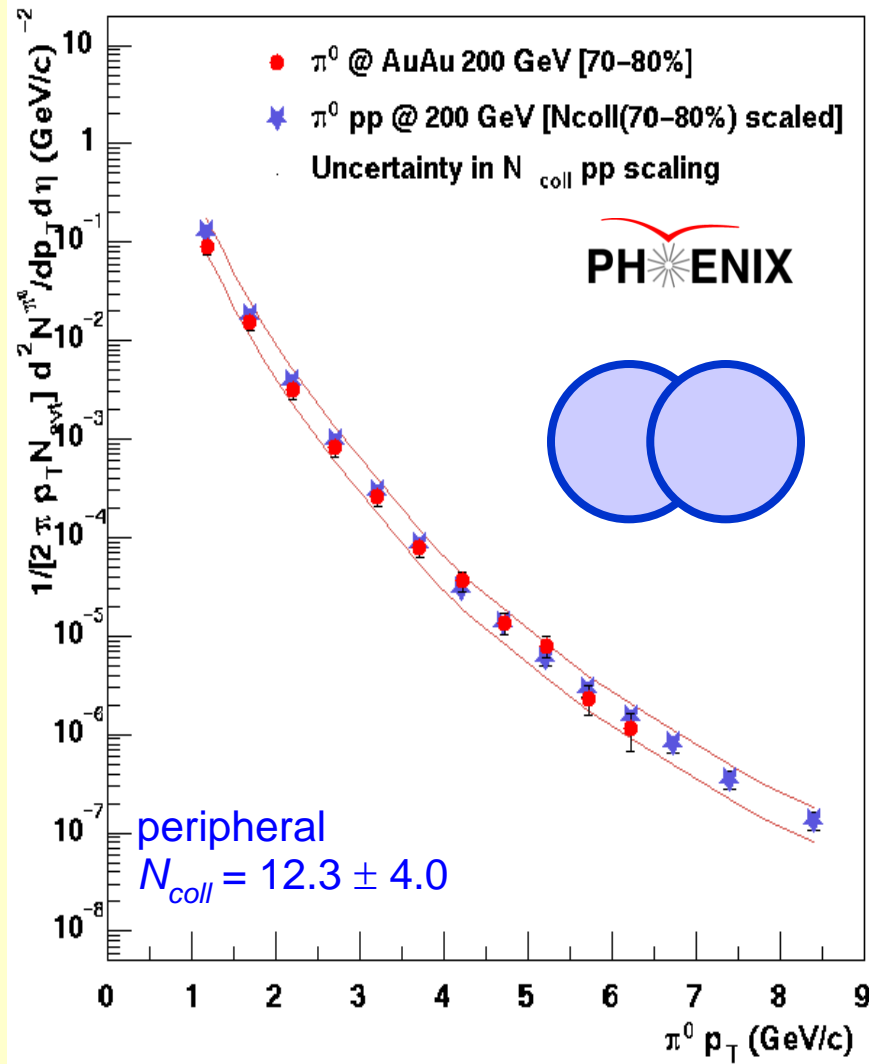
Frank Wilczek

"for the discovery of asymptotic freedom in the theory of the strong interaction"

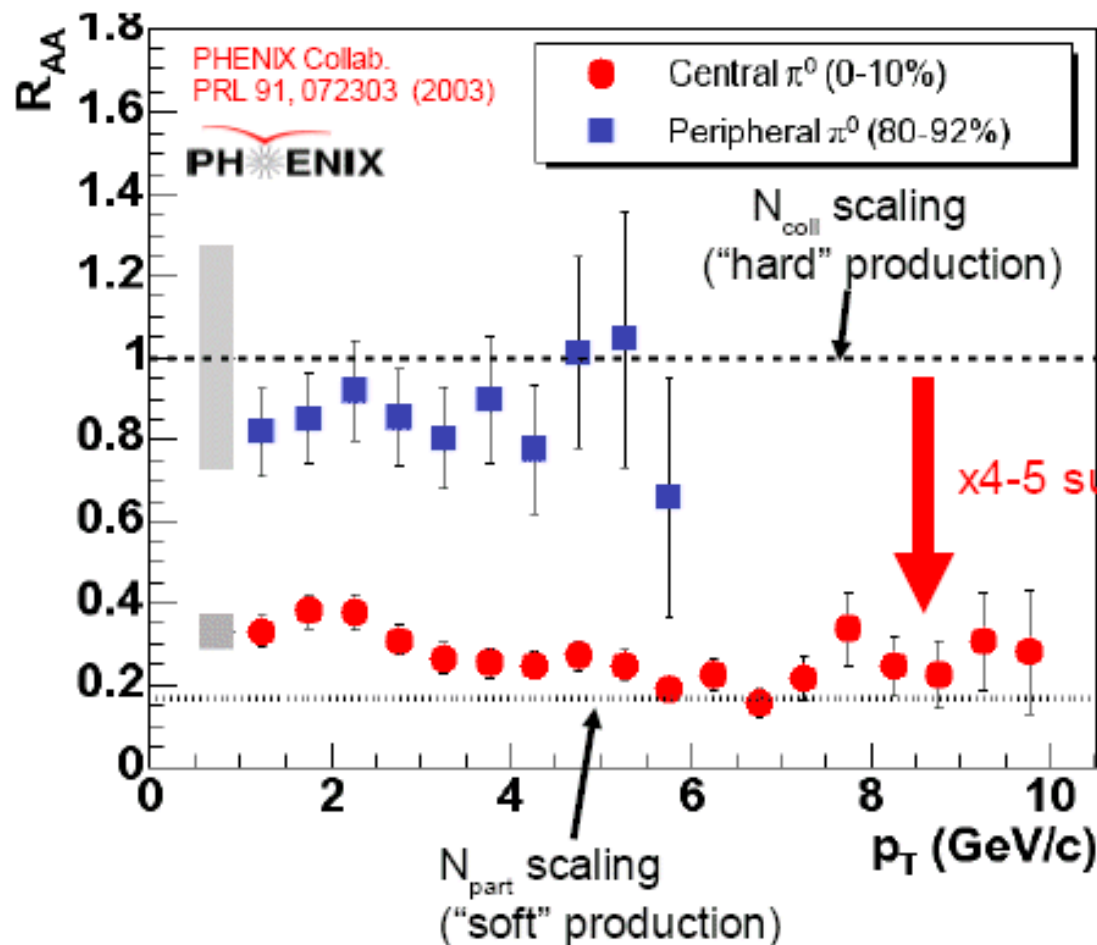
Jets of hadrons produced in high-energy collisions



Early Discovery at RHIC: Strong Suppression

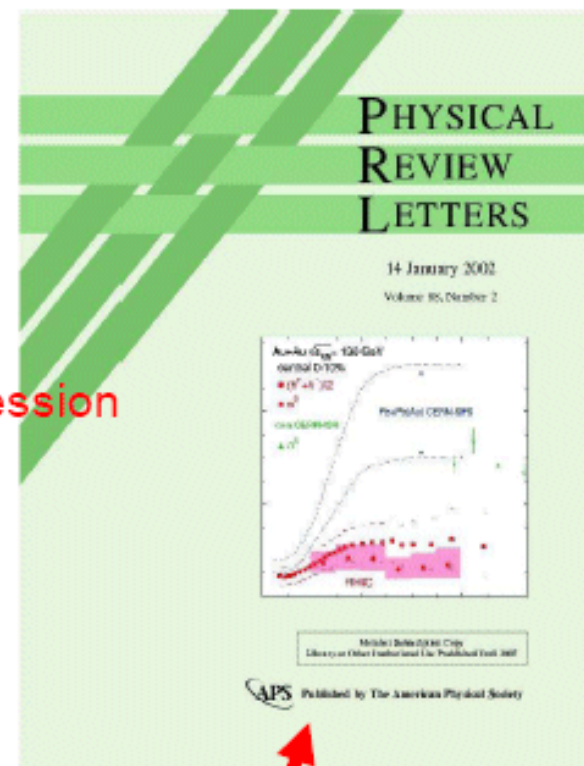


Evidence for a Dense System in Au+Au Collisions



$R_{AA} \ll 1$: well below pQCD (collinear factorization) expectations for hard scattering cross-sections

PRL Cover – 14 January 2002

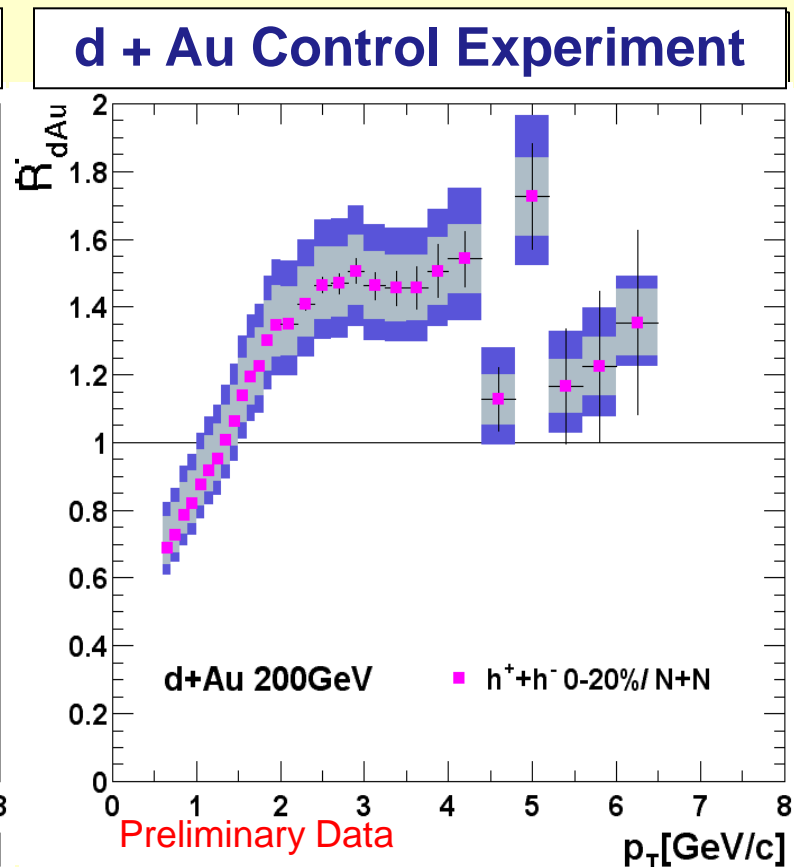
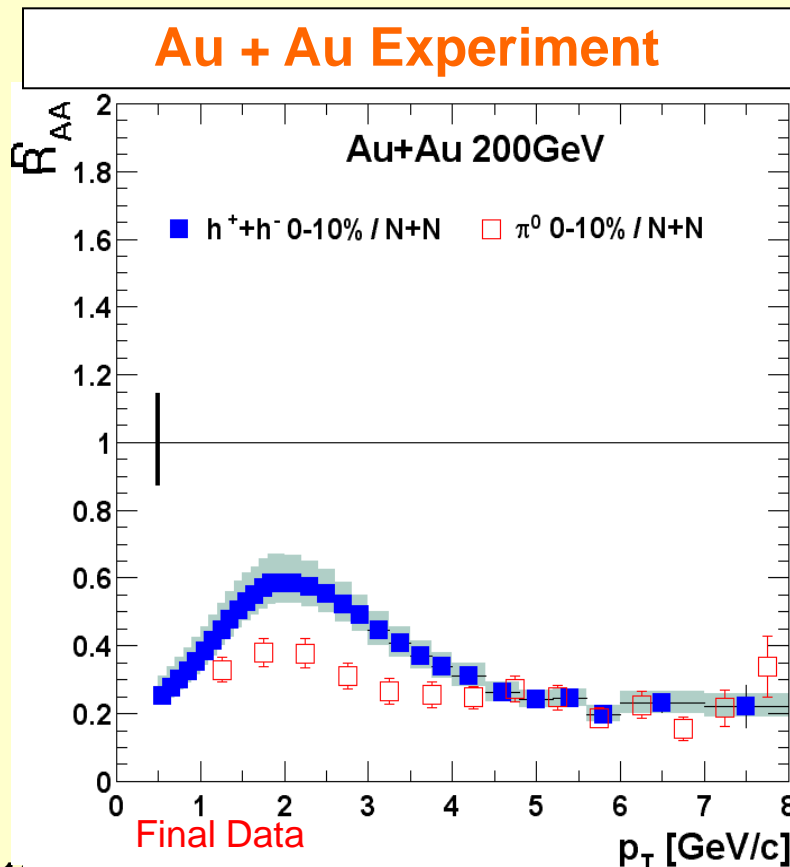


Discovery of
high p_T suppression
(one of most significant
results @ RHIC so far)

Control Experiment: d + Au (cold nucleus)

Some theorists suggested that the observed high p_T suppression in Au+Au central events was an initial state effect. If so, then at least some suppression should also be seen in d + Au collisions.

Experimental results (enhancement) falsified the initial-state conjecture. Conclusion: Au+Au result is a final-state effect.



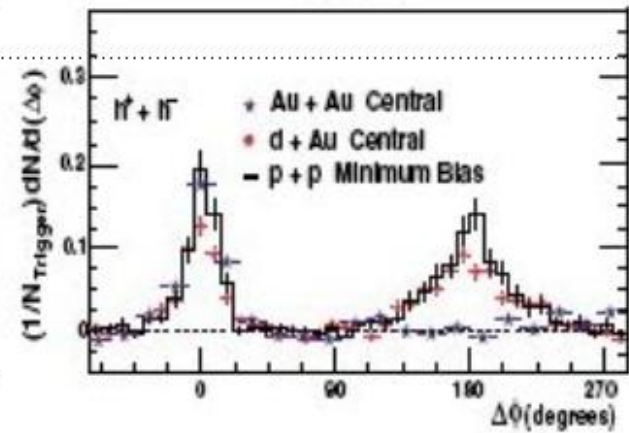
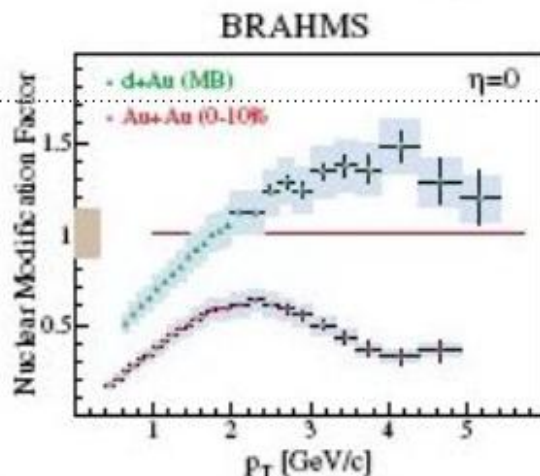
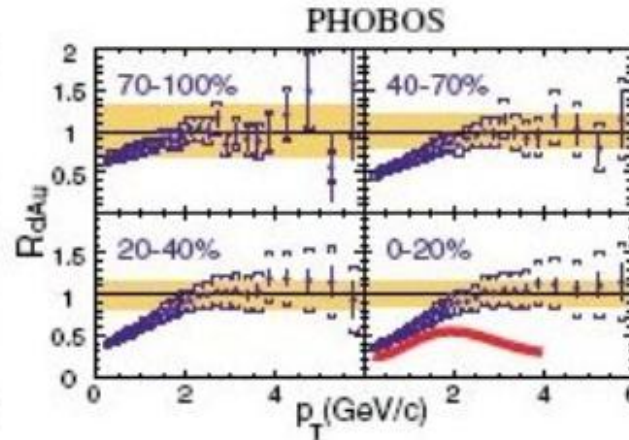
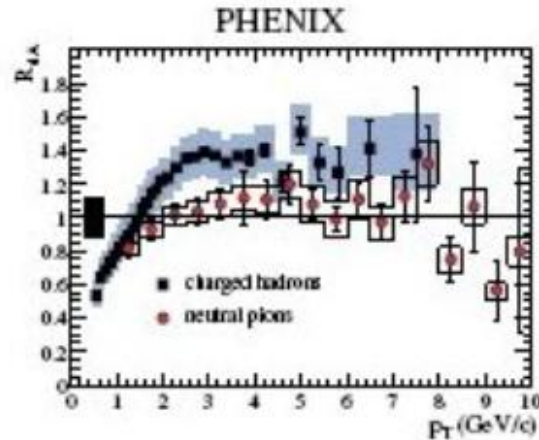
Evidence for a Dense Final State System

d+Au results from



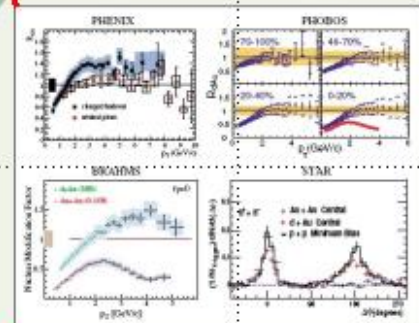
*Presented at a BNL "Press Event"
18 June 2003.*

*PRL Cover
15 August 2003*



PHYSICAL
REVIEW
LETTERS

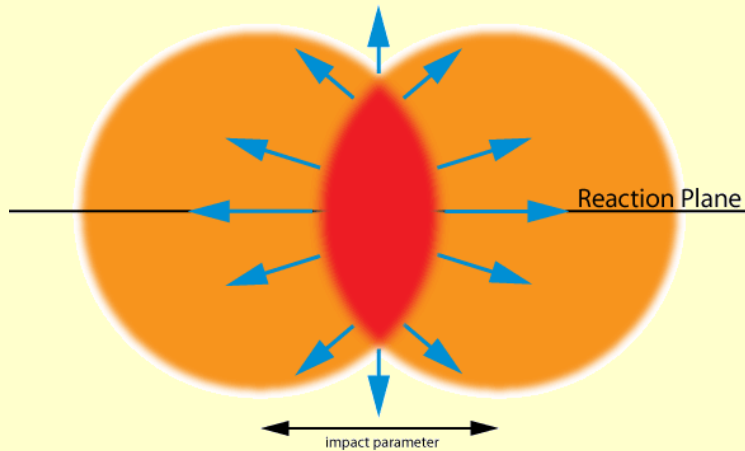
Articles published week ending
15 AUGUST 2003
Volume 91, Number 7



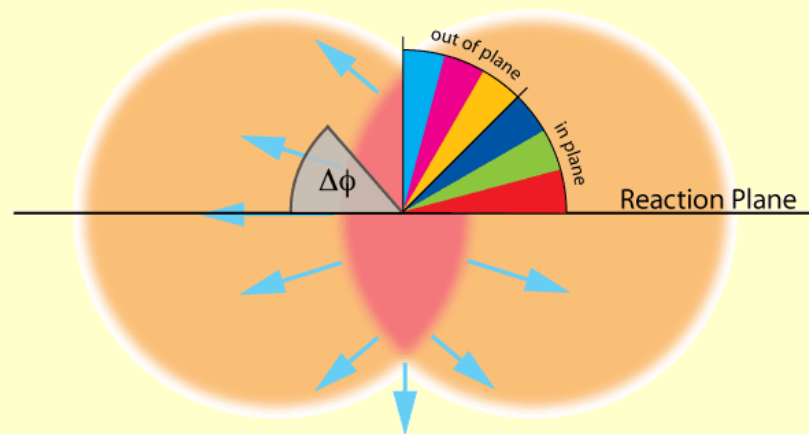
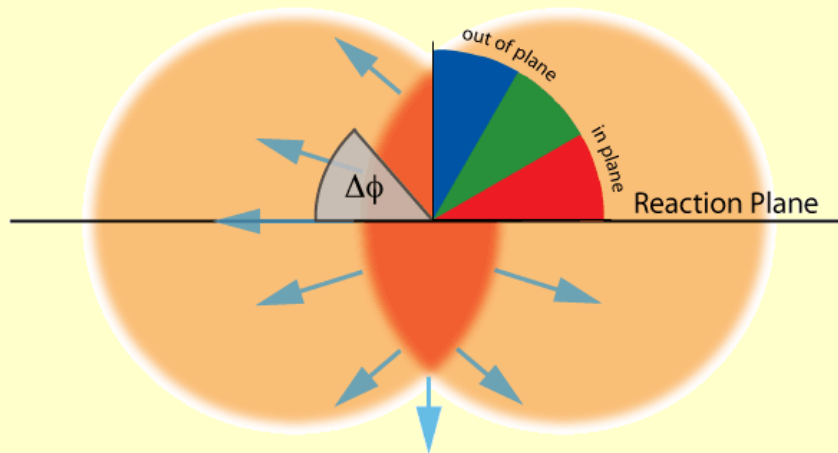
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APS Published by The American Physical Society

Azimuthal Anisotropy



For semi-central collision
Initial spatial anisotropy
evolves into
momentum anisotropy
but **ONLY** if strongly coupled!

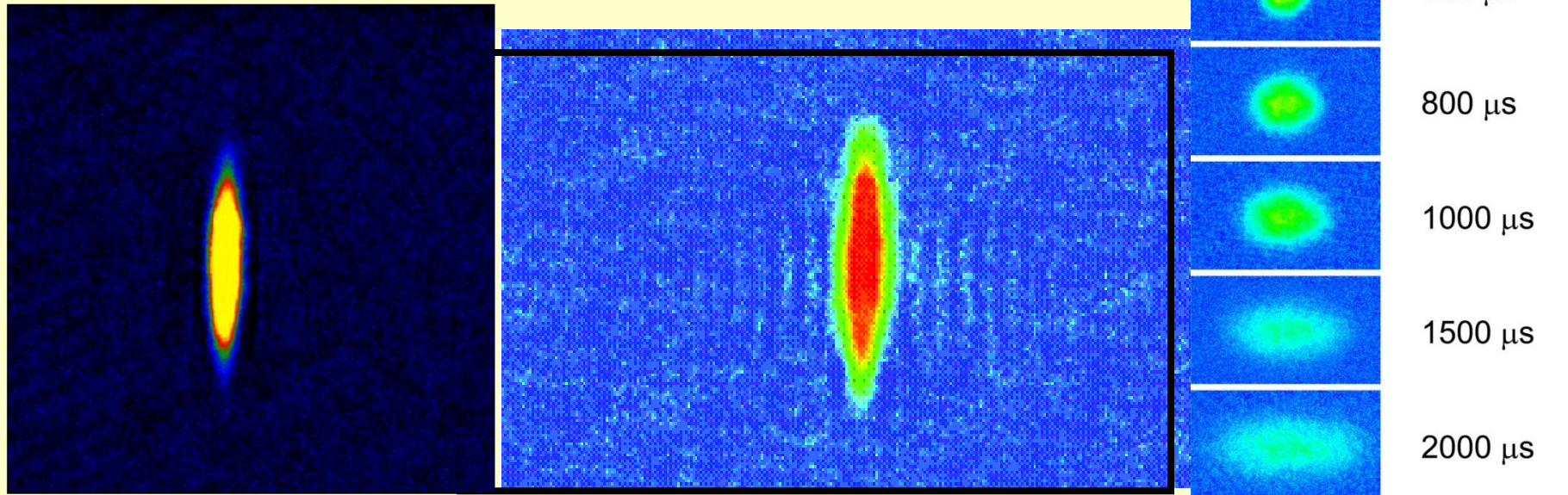


Anisotropic Flow in gases of atoms

Same phenomena observed in gases of strongly interacting atoms. M. Gehm, S. Granade, S. Hemmer, K. O'Hara, J. Thomas. Science 298 2179 (2002)

weakly coupled

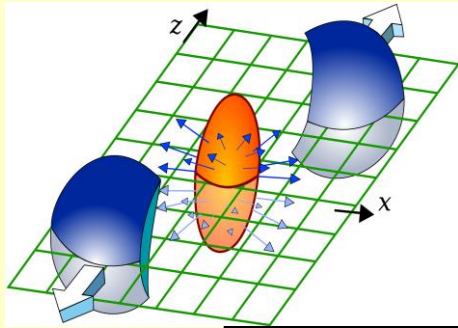
strongly coupled



The RHIC fireball behaves like a strongly coupled fluid

Azimuthal Anisotropy -- Elliptic Flow

Strong Initial Pressure Gradient

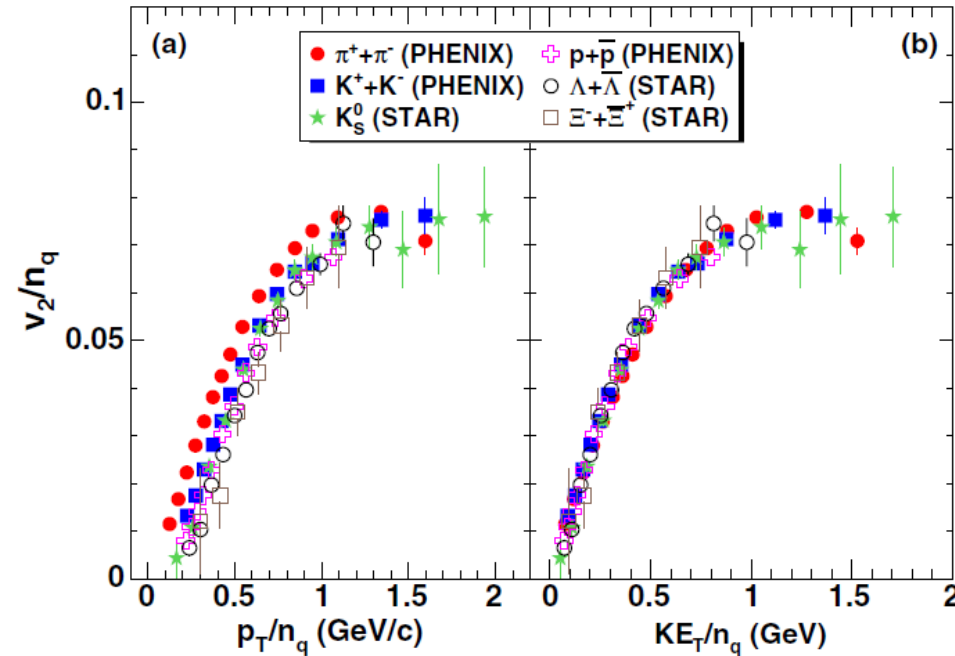
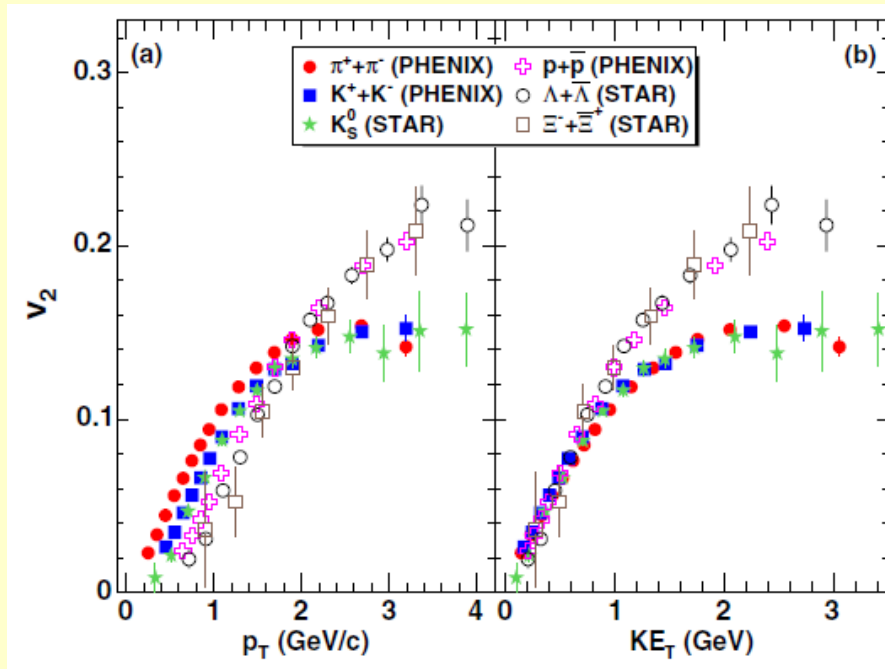
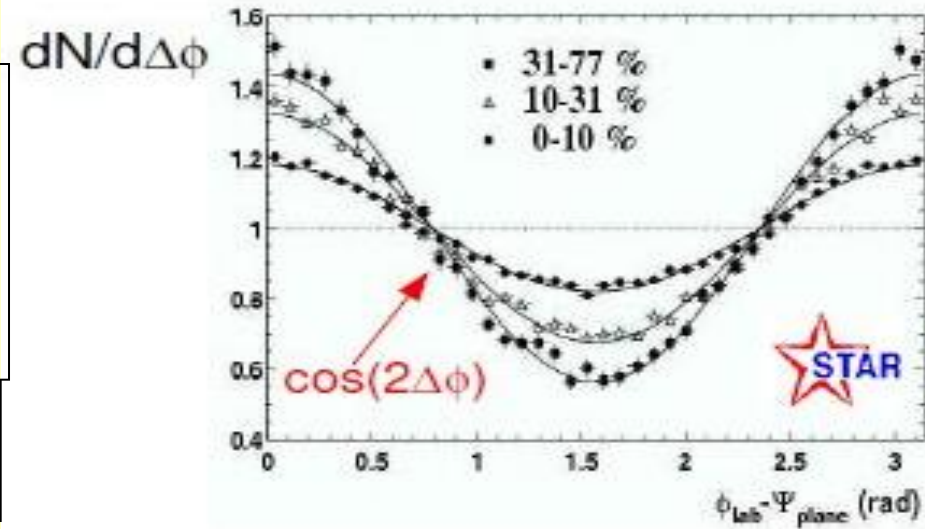


Elliptic Flow

v_2

= 2nd Fourier
Coefficient

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Phi_{RP})$$



RHIC Scientists Serve Up “Perfect” Liquid

RHIC Press Conference held
Monday, April 18, 2005 in Tampa, FL
at the April Meeting of the
American Physical Society.

At least 148 news articles worldwide:



[BBC News](#)



[ABC News](#)



[Interactions.org](#)



[Newsday, April 18](#)



[Michigan State Univ.](#)



[Newsday, April 19](#)



[Scientific American](#)



[Washington Times](#)



[Washington Post](#)



[Nature](#)



[Physics Web](#)



[New York Times](#)



[USA Today](#)



[Xinhua](#)



[TechWhack](#)

Hunting the Quark Gluon Plasma

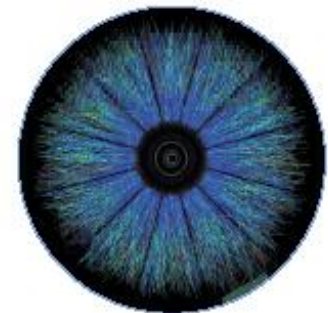
RESULTS FROM THE FIRST 3 YEARS AT RHIC

ASSESSMENTS BY THE EXPERIMENTAL COLLABORATIONS

April 18, 2005



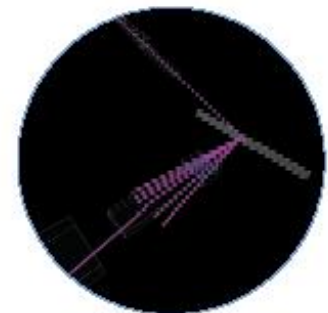
PHOBOS



STAR



PHENIX

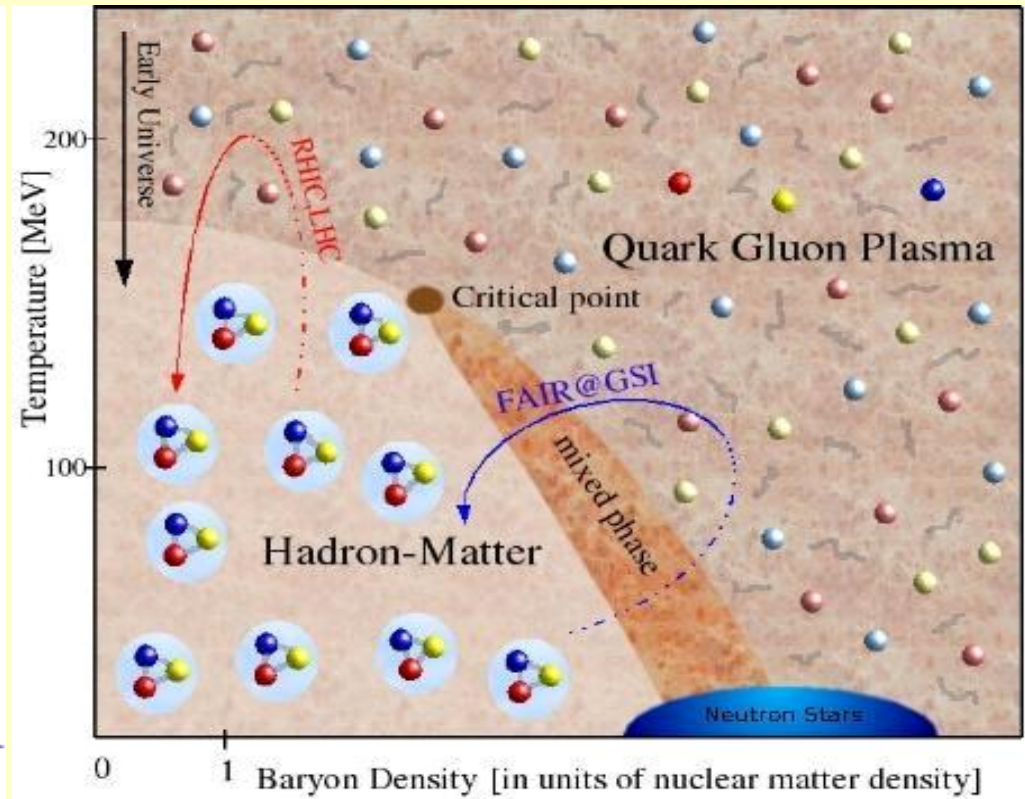
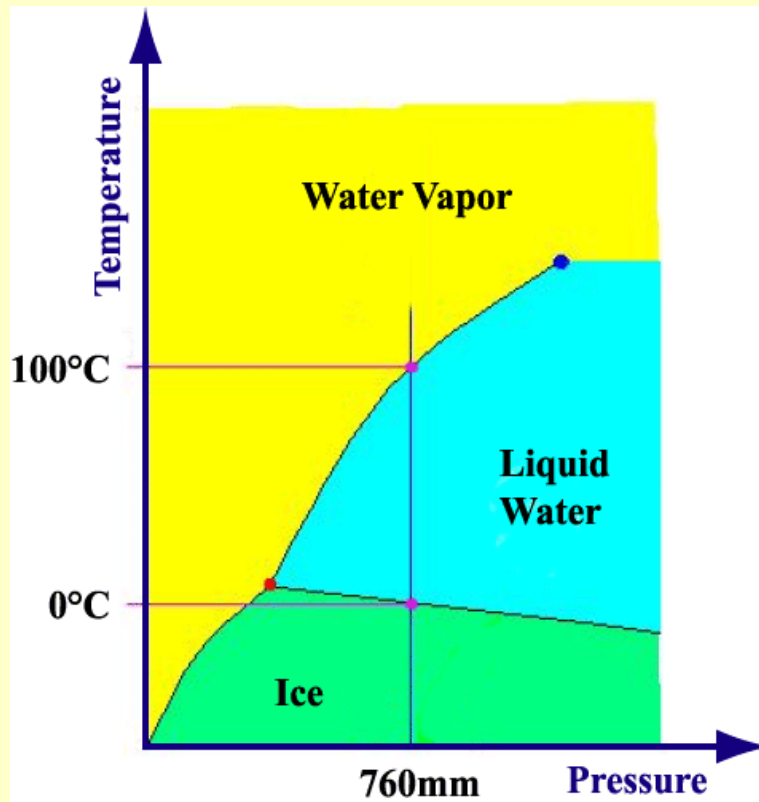


BRAHMS

Relativistic Heavy Ion Collider (RHIC) • Brookhaven National Laboratory, Upton, NY 11974-5000

Ice-Liquid Water-Steam and QCD Phase Transitions

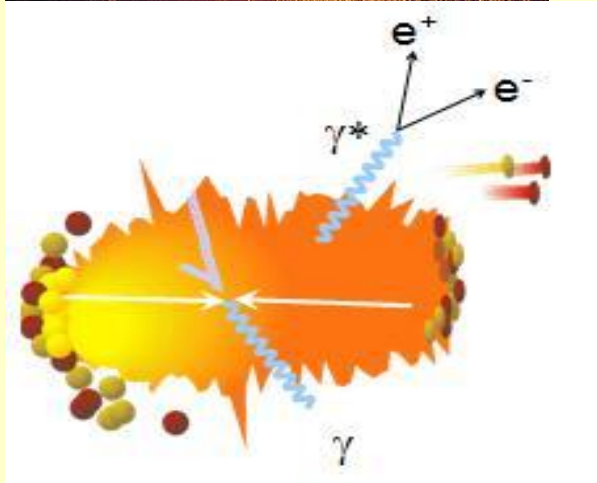
- The colliding nuclei at RHIC energies are expected to melt from bags of protons and neutrons into a collection of quarks and gluons



Goal: Measure the initial temperature of matter formed at RHIC

Is T_{init} higher than $T_c \sim 170 \text{ MeV}$ ($\sim 1 \text{ GeV/fm}^3$)

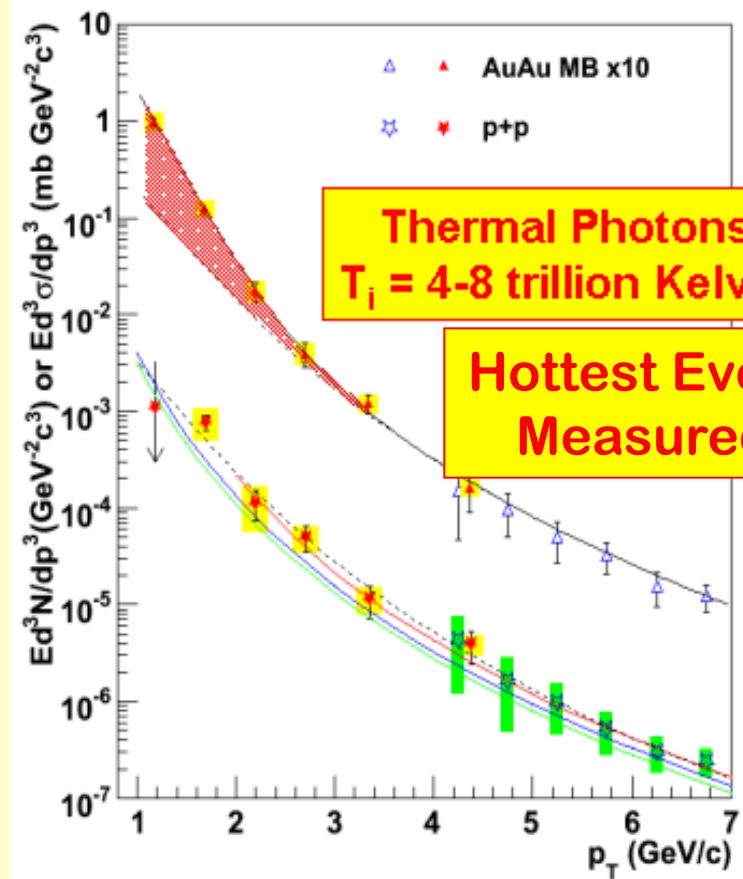
Press event at Feb. 2010 APS Meeting in Washington, DC



Hot matter
emits
Thermal
radiation

Temperature
can be
measured
from the
emission
spectrum

PHENIX



Photon Wavelength

PRL 104, 132301(10); PRC 81, 034911(10)

DISCOVER

Science, Technology, and The Future

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Physics & Math / Subatomic Particles

The Hottest Science Experiment on the Planet

In a Long Island lab, gold particles collide to form a subatomic stew far hotter than the sun.

by Calla Cofield

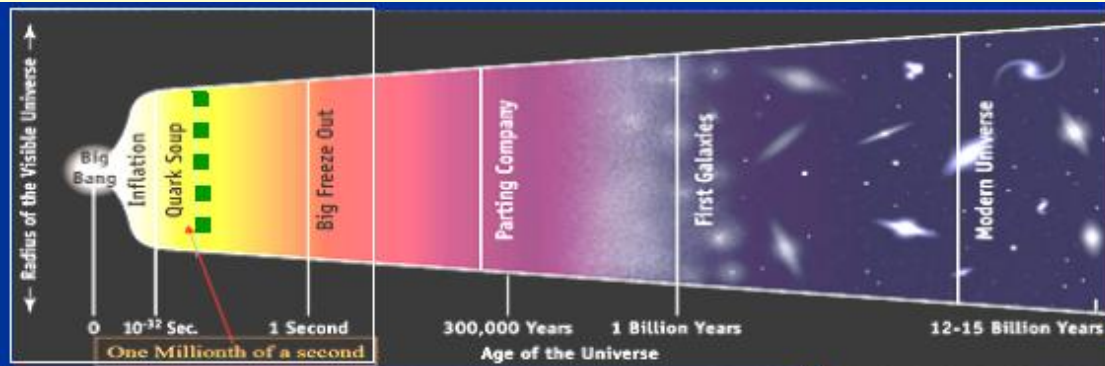
published online February 15, 2010

July 18, 2011
BNL/OEP

Modern Physics: Understanding the very small and the very fast.
Brant Johnson, PHENIX@RHIC/Physics Department/BNL

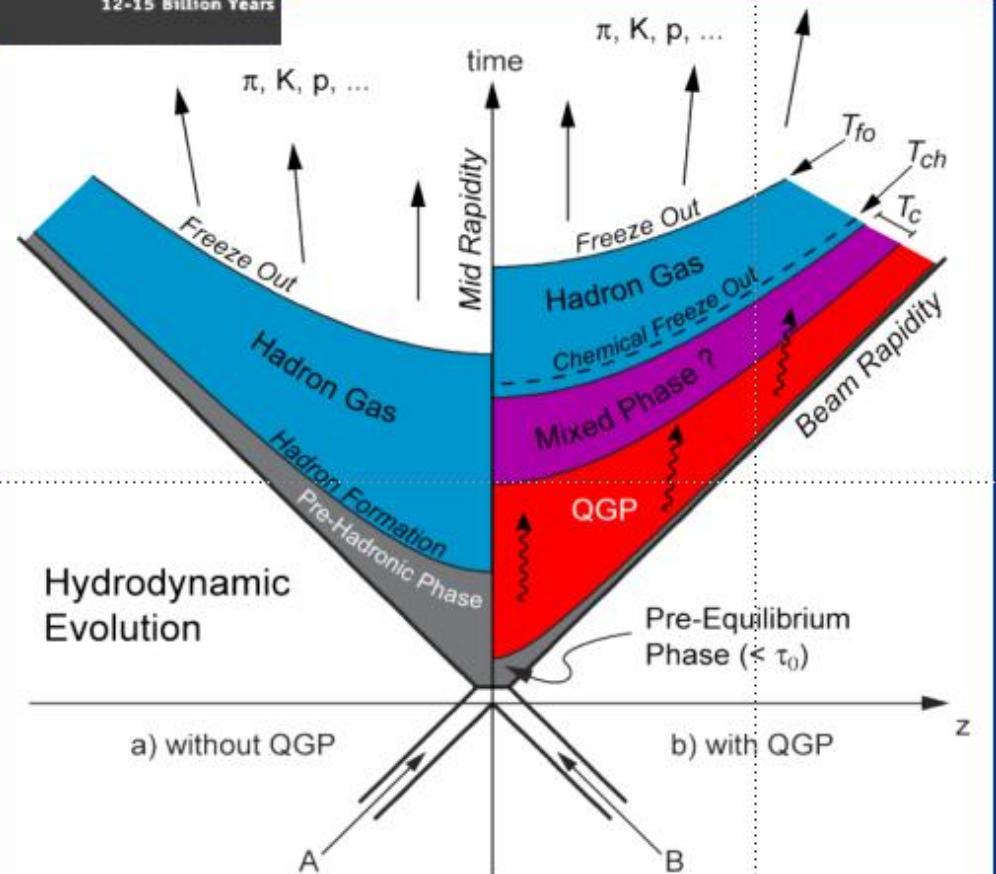
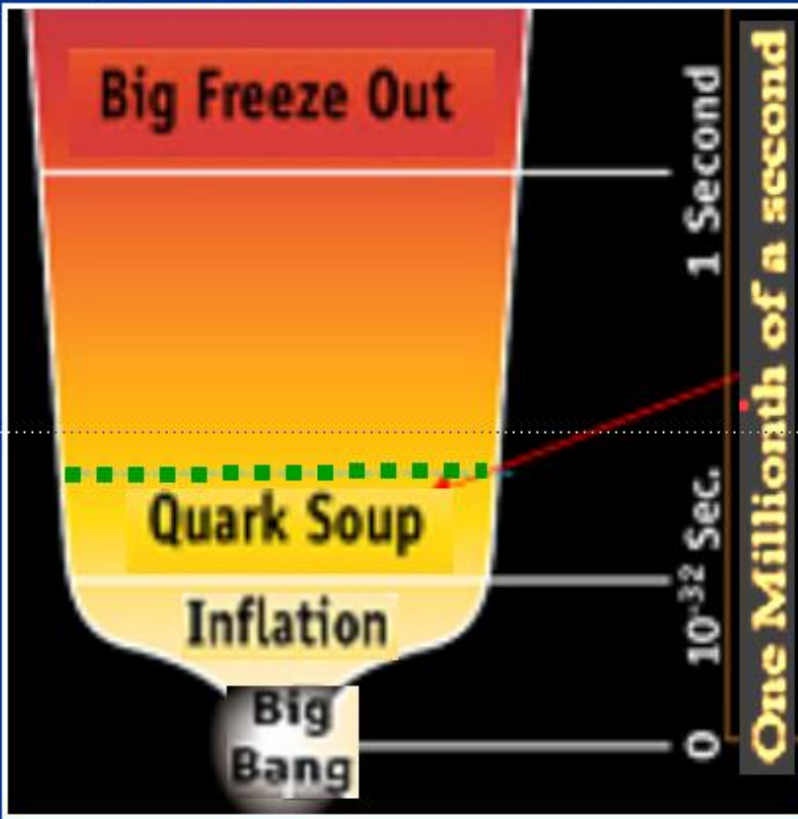
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Physics at a Few Millionths of a Second After the Big Bang

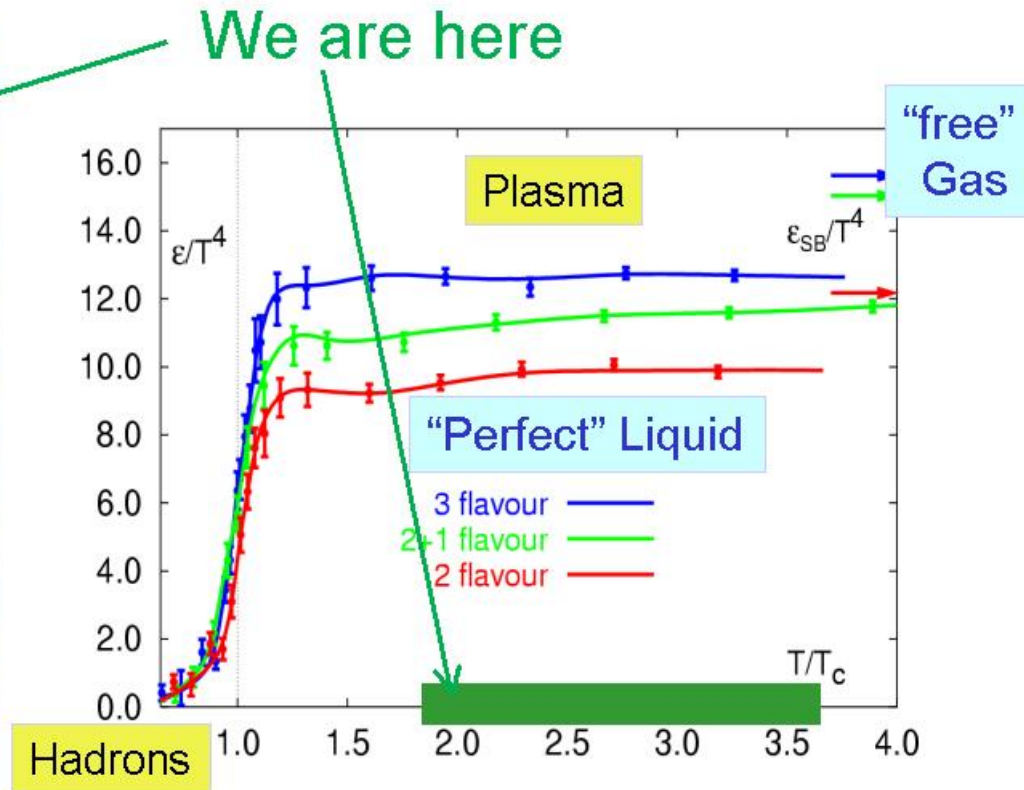
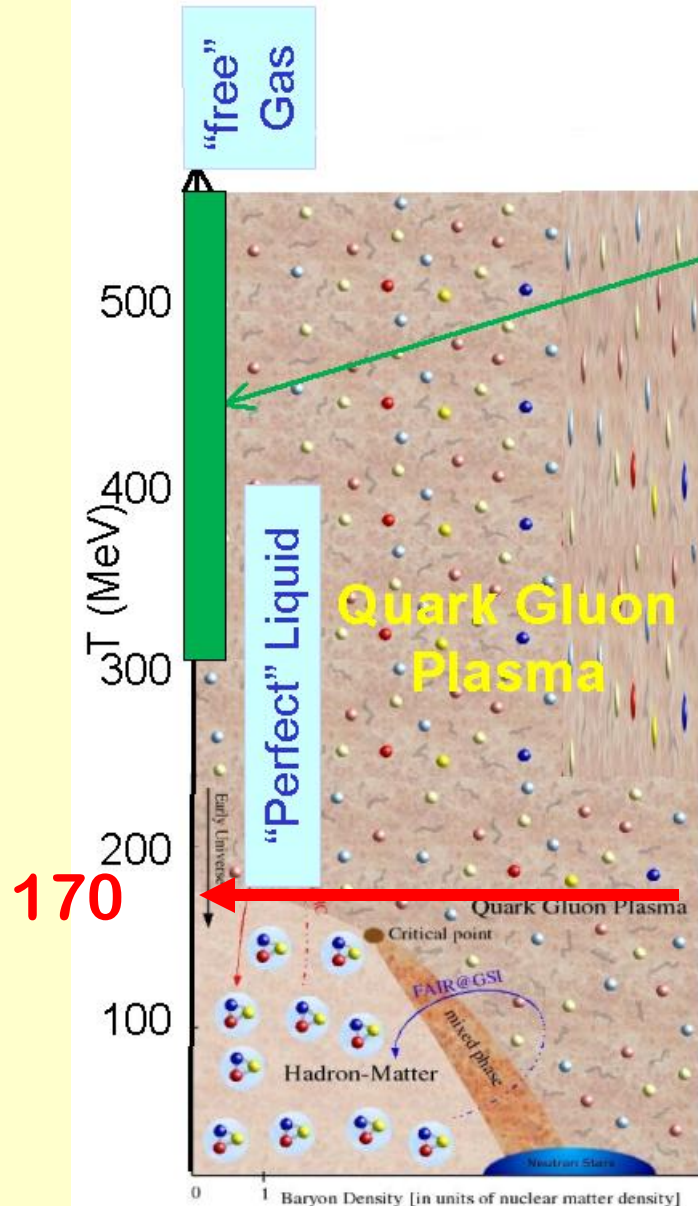


Today is ~14 billion years later.

Most particles detected are hadrons after Freeze Out



Where are we on the QGP map?



$$T_c \sim 170 \text{ MeV}; \epsilon \sim 1 \text{ GeV/fm}^3$$

At these temperature, QGP is *perfect liquid*.

At higher temperature, it can become *gas*

How could string theory be relevant?

The Maldacena duality, known also as AdS/CFT correspondence, has opened a way to study the strong coupling limit using classical gravity where it is difficult even with lattice Quantum Chromodynamics.

It has been postulated that there is a universal lower viscosity bound for all strongly coupled systems, as determined in this dual gravitational system.



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Words to communicate concepts

Brookhaven National Laboratory

Relativistic Heavy Ion Collider

Understanding
Observation
Experiment
Theory
Light Wave
Photon

small, very small
very fast

Mechanics:
Classical
Quantum
Relativistic

The Nucleus

Nucleons:
Proton & Neutron
Radioactive Decay

Particles & Fields
Parton: Quarks
and Gluons
Baryons, Hadrons
 π Meson (pion)

Leptons

Electron e^- Positron e^+
Muon μ^- μ^+ Tau τ^- τ^+
Neutrinos ν_e ν_μ ν_τ

Strong suppression
Dense final state
Anisotropic Flow
Nearly perfect fluid
Asymptotic Freedom
Phase Transitions
Deconfinement
Early Universe
(Big Bang)

The Atom
Hard Sphere Model
Plum Pudding Model
Nuclear Atom
Soft/Hard Scattering
Electron Wave
Wave-Particle Duality
Quantum Mechanics

Direct and Virtual Photons
Hottest Temp. Measured